110 W high stability green laser using type II phase matching KTiOPO_4 (KTP) crystal with boundary temperature control

De-Gang Xu *, Jian-Quan Yao, Bai-Gang Zhang, Rui Zhou, Enbang Li, Shi-Yong Zhao, Xin Ding, Wu-Qi Wen, Yan-Xiong Niu, JuGuang Hu, Peng Wang

College of Precision Instrument and Opto-Electronics Engineering, Institute of Laser and Optoelectronics, Tianjin University, No. 92 Weijin Road, Nankai District, Tianjin 300072, PR China
Cooperated Institute of Nankai University and Tianjin University, Tianjin 300072, PR China
Key Laboratory of Optoelectric Information Science and Technology, Ministry of Education, Tianjin University, Tianjin 300072, PR China

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Abstract

We have developed a diode-pumped high power and high stability green laser. By controlling and stabilizing the boundary temperature of type II phase matching KTP crystal, 110 W high stability green laser output have been achieved. 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 and temperature bandwidth 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, the type II phase matched KTP crystal (optimum phase matching angles are $\Phi = 24.68^\circ$, $\Theta = 90^\circ$ under the condition of phase matching temperature 353 K) was used in the intracavity frequency-doubling resonator. An average output power of 110 W at 532 nm has been achieved with values of 11% and 2% for the optical-to-optical conversion efficiency and the instability, respectively. The optimal boundary temperature of the KTP crystal has been found to be 321.8 K. The experiment results are in good agreement with the theoretical calculation.

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* Corresponding author. Tel.: +86 22 27407676; fax: +86 22 27406436.
E-mail address: xudegang8360@126.com (D.-G. Xu).

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1. Introduction

As well known, most materials have larger absorbance for shorter wavelength lasers. Therefore, high power all-solid-state green lasers generated through frequency conversion technique perform better than IR lasers in many applications, such as marking, precision micro fabrication, trimming, and medical applications. Green lasers have also been used in ocean exploration, laser probes, and underwater communications, etc.

One of the most promising methods to obtain high power green beams is using intracavity second-harmonic-generation (SHG) scheme based on the use of nonlinear crystals. KTiOPO$_4$ (KTP) is an excellent nonlinear crystal with a high nonlinear conversion coefficient, high-allowed angles and temperatures, small walking-off angles and a relatively high damage threshold. KTP crystal has been widely used to generate the second-harmonic-wave green light in the intracavity frequency doubling Nd:YAG. Le Garrec et al. [1] employed a Z-cavity to demonstrate an output power of more than 100W 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-optic 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 a KTP crystal. Stable CW green power of 27 W was generated in a diode-side-pumped intracavity-frequency-doubled CW Nd:YAG. Jonghoon 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 a 25.4% optical to optical efficiency. However, all the published research works did not show the instability of green beam caused by the thermal effect in the KTP crystal at a high power level.

Since the KTP crystal absorbs the fundamental and the second harmonic (SH) waves power, the temperature distribution in the KTP crystal will become non-uniform and the phase-matching condition at room temperature will shift. The frequency-doubling efficiency will decrease significantly because optimal phase-matching angles are changed at different positions inside the KTP crystal. As a consequence, the output power becomes unstable. Jianan Zheng et al. [5] theoretically analyzed the influence of the thermal effect on the conversion efficiency and the intensity profile of the type-II phase matching SH wave in a 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. Yao Jian-Quan et al. [6] reported a method to tilt the KTP crystal to compensate the phase mismatching. However, the SH beams will be separate due to the reflection of the KTP crystal in an intracavity frequency-doubled when the crystal is tilted. We [7] also obtained an 85-W green output by reducing the boundary temperature of KTP to 277 K, leading to a 1.03% instability. However, it is likely to generate ‘graying track’ inside the KTP crystal and appear the condensation at the surface of the crystal under the condition of low temperature, leading to a low conversion efficiency and a low damage threshold.

In this paper, we analyze the KTP crystal temperature distribution by solving thermal conduction equation. The phase matching angles and allowed temperatures are calculated by using the temperature derivative of refractive indices in a KTP crystal. The SH conversion efficiency of KTP is also analyzed at different temperatures. From the calculate results, we identify the optimal boundary temperature, at which the center temperature of the KTP crystal can stabilize at the optical phase matching temperature, hence increasing the conversion efficiency and the output beam stability. In the experiment, a 110-W high stability green laser output was obtained in a diode-side-pumped Nd:YAG laser by setting the boundary temperature of KTP at 321.8 K. The 110 W average output power was generated at a repetition rate of 10.6 kHz when the Nd:YAG rod was pumped by laser diodes with a total power of 1 kW, leading to a 11% optical-to-optical conversion efficiency and less than 2% instability.
2. Theoretical calculations

In an intracavity frequency-doubled Nd:YAG laser, the thermal power in the KTP crystal is uniform along the direction of beams because the fundamental wave is processing frequency conversion in the dual-direction of the KTP crystal, which improves the frequency conversion efficiency. Therefore, the variations of temperature along the axial direction will be neglected when analyzing the temperature distributions 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],

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{Q}{K},
\]

where \(x, y\) indicate the positions inside the KTP crystal; \(T\) is the temperature at different positions inside the KTP crystal; \(K\) is thermal conductivity.

In Eq. (1), \(Q\) is the calorific power, and its expression is described with

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

where \(P\) is the absorbed power of the fundamental wave; \(\alpha\) is the absorption coefficient; \(l\) is the length of the KTP crystal; \(r_0\) is the dimension of laser beam inside the KTP crystal.

The calculated temperature distributions inside the KTP crystal are depicted in Fig. 1. In the calculations, we used the following parameters: the size of the KTP crystal is \(6 \times 6 \times 9.2\) mm; the power of the fundamental wave \(P_{1064}\) is 180 W; the power of the SH wave \(P_{532}\) is 110 W; their absorption coefficient are \(\alpha_{1064} = 0.01\%\) cm\(^{-1}\) and \(\alpha_{532} = 1.0\%\) cm\(^{-1}\) individually; and the radius of the fundamental wave beam \((r_0)\) is 3 mm.

It is well known that the frequency conversion efficiency depends on the phase matching condition. To illustrate the influence of crystal thermal effect on the phase matching condition, a theoretical study of Nd:YAG SHG using a KTP crystal was carried out. The refractive indices on the fast- and slow-axis for the fundamental wave in the principal plane XOY of KTP are given by [9],

\[
\begin{aligned}
\begin{cases}
\left(\frac{\partial n_{\phi}}{\partial \phi}\right) = 0,
\end{cases}
\end{aligned}
\]

\[
\begin{aligned}
\begin{cases}
\left(\frac{\partial n_{\phi}}{\partial \phi}\right) = \sqrt{\frac{(n_{\phi}^{(1)} \cos \phi)^2 + (n_{\phi}^{(2)} \sin \phi)^2}{n_{\phi}^{(1)}}},
\end{cases}
\end{aligned}
\]

where \(n_x, n_y, n_z\) are the principal values of refractive indices and are functions of wavelength, \(\lambda\) (\(\mu\)m) and crystal temperature, \(T\) (K). The temperature derivative of the refractive indices in the KTP crystal are given by [10]:
\[
\frac{dn_X}{dT} = (0.1323\lambda^{-3} - 0.4385\lambda^{-2} + 1.2307\lambda^{-1} + 0.7709) \times 10^{-5} \text{ (K}^{-1}) 
\]
\[
\frac{dn_Y}{dT} = (0.5014\lambda^{-3} - 2.0030\lambda^{-2} + 3.3016\lambda^{-1} + 0.7498) \times 10^{-5} \text{ (K}^{-1}) 
\]
\[
\frac{dn_Z}{dT} = (0.3896\lambda^{-3} - 1.3332\lambda^{-2} + 2.2762\lambda^{-1} + 2.1151) \times 10^{-5} \text{ (K}^{-1}),
\]
where \(\lambda\) is in \(\mu\text{m}\), and \(dn_X/dT, dn_Y/dT, dn_Z/dT\) are in \(\text{K}^{-1}\). Phase matching angle \(\phi_{pm}\) is obtained by solving Eqs. (3) and (4) under the condition of \(n^{e_1}_{el} + n^{e_2}_{el} = n^{e_1}_{el}\) for different phase matching temperature \(T\). Fig. 2 appears the phase matching angles as a function of temperature. When the temperature of the nonlinear crystal is changed, the temperature phase-matching bandwidth \(\Delta T \cdot l\) (FWHM) for SHG can be easily calculated from [10]

\[
\Delta T \cdot l = \frac{2\lambda_l}{2.25} \left\{ \frac{\partial n^{e_1}}{\partial T} + \frac{\partial n^{e_2}}{\partial T} - 2 \frac{\partial n^{e_2}_{el}}{\partial T} \right\}^{-1},
\]

where \(\lambda_l\) is the wavelength of the fundamental wave, \(\partial n_i/\partial T\) and \(\partial n_{el}/\partial T\) are the temperature derivatives of the refractive indexes for the fundamental and second-harmonic frequencies, respectively, and the superscripts \(e_1\) and \(e_2\) represent the polarization directions of the interacting wavelengths (\(n^{e_1} > n^{e_2}\)) [11]. Plotted in Fig. 3 are the temperature bandwidth \(\Delta T \cdot l\) of type-2 KTP as a function of temperature.

The center temperature of the KTP crystal will change with the boundary temperature because of heat transfer. From Fig. 2, it can be seen that the temperature difference between the center and the boundary is about 35 K, which is larger than the allowed phase matching temperature of the KTP crystal, hence the SHG efficiency will decrease. In the intracavity resonator, the power intensity distribution of the fundamental wave is a like-Gaussian 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. Fig. 4 shows the normalized SHG efficiency as the function of temperature in the KTP crystal (the phase matching temperature is 353 K and the phase matching angles are \(\phi = 24.68^\circ, \Theta = 90^\circ\)).

3. Results and discussion

In our experiment, we used a diode laser pump module made by CEO, Inc. The pump module consists of 80 diode bars (808 nm wavelength, 20 W output power), with a pentagon pump model.
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 a plano-concave cavity structure in order to achieve high stability output and to increase the output power. The experiment set-up is shown in Fig. 5. The total cavity length is 550 mm. The dimensions of the Nd:YAG rod is 6.36 mm × 136 mm. An acousto-optic modulator (provided by NEOS Inc., USA) with a high diffraction efficiency is used as a Q-switch. The laser was operated at a repetition rate of 10.6 kHz. The dimension of the KTP crystal (from CSK Photonics Co. Ltd., Jinan, China PR) is 6 mm × 6 mm × 9.2 mm. The crystal was coated with a dual-wavelength antireflection coating and was placed between output mirror \((T > 98\% \text{ at } 532 \text{ nm}, R > 99.5\% \text{ at } 1064 \text{ nm}, \text{where } T \text{ is transmission and } R \text{ is reflection})\) and harmonic separator mirror \((R > 99.5\% \text{ at } 532 \text{ nm}, T > 98\% \text{ at } 1064 \text{ nm})\). The phase matching angles of the KTP crystal are \(\Phi = 24.68^\circ, \Theta = 90^\circ\) (which are type II phase matching angles at a temperature of 353 K). Its boundary temperature was controlled in the oven by a digital temperature controller (from Fuji Inc., Japan). The optimal phase matching temperature in the center part of the KTP crystal was reached and stabilized by controlling its boundary temperature.

In the experiment, when the temperature of the heating oven was adjusted, the green output power fluctuated. When the boundary temperature was decreased, the output power decreased as shown in Fig. 6. The green output power fell down by about 10 W and became unstable when the center temperature of KTP crystal was changed from 358 to 341 K. As can be seen from Fig. 6, in the temperature range from 358 to 353 K, the variations of green output power are not obvious. This is because the temperature of the center part of the KTP crystal is in the optimal phase matching temperature and the temperatures of other parts are also within temperature bandwidth although the SHG efficiency of those parts is rather low. Therefore, the SHG efficiency of total fundamental wave is relatively high. The experiment results are in good agreement with the theoretical calculations. In order to make the output power stable, we kept the heating oven of the KTP with a long-term stability of ±0.1 °C. When the pumping power was 1000 W and the repetition rate was 10.6 kHz, the maximum output green power was 110 W with a
pulse width of 110 ns under the KTP crystal heating oven at 321.8 K.

At 100 W green output power, the green laser remained stable for at least 5 h of operation, with an output power fluctuation of less than 2% and a pulse-to-pulse instability of 5%. We believe that our technology of employing high operating temperature KTP crystal and precisely controlling its boundary temperature effectively have suppressed the instability. Fig. 7 shows the green beam output power and pulse width as functions of diode pumping current. Fig. 8 gives the distribution of green beam at 110 W output power.

4. Conclusion

In conclusion, we have developed a 100-W high-stability green laser by controlling the boundary temperature of the KTP crystal (type II phase matching angle is $\phi = 24.68^\circ, \Theta = 90^\circ$, at temperature 353 K) in a diode-side-pumped Nd:YAG intracavity frequency doubled laser system. The maximum average 532 nm output power of 110 W has been generated with values of 11.5% and 2% for the optical-to-optical and the instability, respectively, when the boundary temperature of KTP was set at 321.5 K and the pumping power was 1000 W, at a repetition rate of 10.6 kHz.

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