Investigation of the thermal lens effect of the TGG crystal in high-power frequency-doubled laser with single frequency operation

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Abstract: The thermal lens effect of the TGG crystal is investigated theoretically and experimentally. The theoretical analysis is demonstrated by the experimental measurements on a home-made frequency-doubled Nd:YVO_4 laser with single-frequency operation. In the presence of the thermal lens effect of the TGG crystal, the output power can be optimized by shortening the distance between the cavity mirrors of M_3 and M_4 (two plane-concave mirrors placed at two sides of the second-harmonic generator). Consequently, a single-frequency laser with output power of 18.7 W at 532 nm is obtained. The power stability and the beam quality M^2 are better than $\pm 0.4\%$ for 5 hours and 1.08, respectively. Meanwhile, we observe and discuss a bistability-like phenomenon of the laser in the cases of increasing and decreasing the incident pump power.

OCIS codes: (140.3410) Laser resonators; (140.3515) Lasers, frequency doubled; (140.3560) Lasers, ring; (140.3570) Lasers, single-mode; (140.6810) Thermal effects.

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#232027 - $15.00 USD Received 7 Jan 2015; revised 8 Feb 2015; accepted 9 Feb 2015; published 17 Feb 2015

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1. Introduction

All-solid-state single-longitudinal-mode (SLM) lasers have been widely utilized in science and technology fields because of their high output power, perfect beam quality, low intensity noise and so on. For a SLM laser with high output power, a ring resonator involving an optical diode is generally employed since in such traveling-wave resonators the harmful spatial hole burning effect is eliminated and thus SLM operation can be possibly realized [1]. The optical diode is usually composed of a Faraday rotator and a half-wave plate, and Faraday rotator is made up of a magneto-optical medium surrounded by a permanent magnet. Terbium Gallium Garnet (TGG) crystal is an attractive choice for Faraday rotator owing to its high Verdet constant, favorable thermal conductivity, low transmission loss and high laser-damage threshold [2]. In the past researches, the thermal effects of the gain medium have been investigated vastly and deeply, and lots of technical improvements have been exploited to reduce thermal effect in the gain medium [3–7]. Our group recently compensated the astigmatism of the ring cavity via that introduced by the thermal lens effect of the gain medium and achieved astigmatism self-compensation of the laser [8]. However, the thermal effect of the TGG crystal has not been paid much attention since the absorption of the intracavity laser radiation of the TGG crystal is far less than that of pump light of the laser crystals. The current studies on the thermal effect of TGG crystals are mainly concentrated in the giant system of gravity wave detection [9–12], where Faraday isolator is utilized to isolate the pre-stabilized laser (PSL) from the backscattering light of the main interferometer. When TGG crystal is illuminated by the laser beam with high power, its thermal effect caused by the absorption of the laser can't be disregarded, which results in the decline of isolation ratio and influences the mode matching between the PSL and the main interferometer. Similarly, the laser power in the resonator of the solid state lasers can reach up to hundreds or even thousands of watts and further more the fundamental beam in the TGG crystal is tightly focused to only a fraction of a millimeter. Even if the absorption of the fundamental light of the TGG crystal is quite low, the influence of its thermal effect can't be neglected. To the best of our knowledge, few literatures have discussed the influence of the thermal effects of the TGG crystal in high-power single-frequency solid-state lasers, thus far.

In this paper, we firstly introduced the mechanism of the thermal lens effect of the TGG crystal and then analyzed its influence on the laser. On this base, a laser system was designed to demonstrate the theoretical calculation. By shortening the distance between two cavity mirrors (M_3 and M_4) placed at two sides of the second-harmonic generator (L_{34}), the output power can be optimized and a stable and single-frequency laser with output power of 18.7 W at 532nm was obtained. The long term stability of the output power and beam quality M^2 were better than $\pm 0.4\%$ for 5 h and 1.08, respectively. Meanwhile, a bistability-like phenomenon of the laser was observed and discussed in the cases of increasing and decreasing the incident pump power.

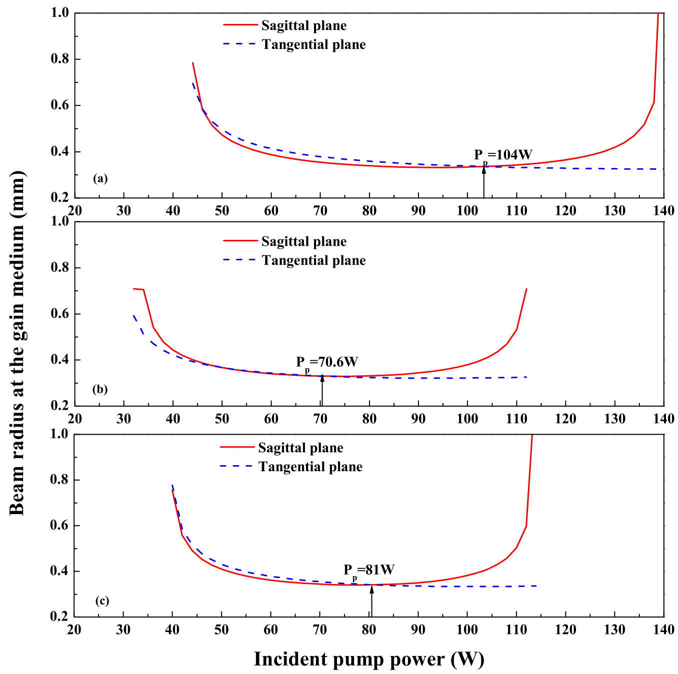

Fig. 1. Beam radius at gain medium. (a) L_{34}=101 mm without considering the thermal lens effect of the TGG crystal, (b) L_{34}=101 mm with considering the thermal lens effect of the TGG crystal, (c)L_{34}=97 mm with considering the thermal lens effect of the TGG crystal.

2. Theoretical analysis

In a SLM laser system with high output power, the TGG crystal is often installed in the aperture of a permanent magnet mounted on the cavity by a copper oven and the fundamental beam pass through the TGG crystal along its central axis. Therefore, the TGG crystal is longitudinally illuminated by continuous wave laser radiation and its periphery temperature is constant because the cavity temperature is controlled by thermoelectric cooler (TEC). The thermal conductivity of the magnet and the copper oven is much greater than that of the TGG crystal, so the heat flow is essentially radial. In addition, the heat dissipation of the TGG rod end-face is negligible. As a result, the heat model described in reference [3] can be applied to the TGG crystal in our laser system and the thermal focal length of the TGG crystal can be expressed as:

$$f = \frac{\pi K_c \omega_T^2}{\eta P \frac{dn}{dt}} \frac{1}{1-\exp(-\alpha l)} \tag{1}$$

where K_c and dn/dt are the thermal conductivity coefficient and thermo-optical coefficient of the TGG crystal, respectively, η is thermal conversion coefficient, which equals to unity because the absorbed laser radiation by the TGG crystal is overall converted to heat. P is the intracavity power of the laser, α and l are the absorption coefficient and the length of the TGG crystal, respectively. ω_T is the radius of the laser beam at the TGG crystal. In our laser system, the TGG crystal located tightly close to the gain medium and the divergence angel of the fundamental beam at the position of the gain medium is rather small, so the beam radium in the TGG crystal is essentially equal to that in the gain medium and basically keeps a constant value with the variation of L_{34} at the optimal operating point of the laser.

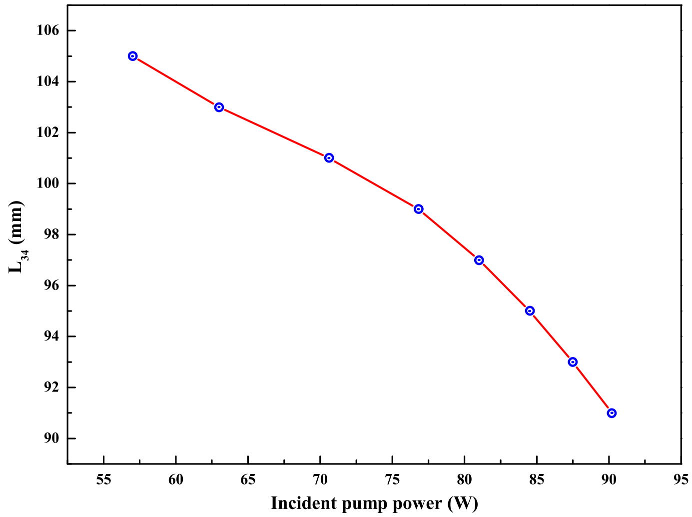

Fig. 2. Theoretical value of L_{34} versus the allowable incident pump power.

Based on the oscillating condition of intracavity frequency-doubling lasers [13], the intracavity power of the laser is:

$$P = \pi\omega^2 \frac{-(\frac{L}{I_0}+K_{NC}) + \sqrt{(\frac{L}{I_0}+K_{NC})^2 - 4\frac{K_{NC}}{I_0}(L-g_0 l_0)}}{\frac{2K_{NC}}{I_0}} \tag{2}$$

where L is the round-trip linear loss, I_0 is the saturation power density, K_{NC} is the nonlinear conversion coefficient, g_0 is the small signal gain coefficient, l_0 is the gain medium length, ω is the beam radius at the position of the gain medium. From Eq. (1) and Eq. (2), the thermal focal length of TGG crystal is:

$$f = \frac{K_c\omega_T^2}{\eta\omega^2 \frac{-(\frac{L}{I_0}+K_{NC})+\sqrt{(\frac{L}{I_0}+K_{NC})^2-4\frac{K_{NC}}{I_0}(L-g_0 l_0)}}{\frac{2K_{NC}}{I_0}} \frac{dn}{dt}} \frac{1}{1-\exp(-\alpha l)} \tag{3}$$

In order to analyze the influence of the thermal lens effect of the TGG crystal on the stable range of the laser, the mode size in the gain medium as a function of the pump power is calculated by the *ABCD* matrix under the approximation of a thin lens in the middle of the TGG crystal, which is shown in Fig. 1, where the thermal lens effect of the gain medium has been taken into account [8]. The physical parameters used for Fig. 1 are $K_c = 7.4Wm^{-1}K^{-1}$, $dn/dt = 20\times10^{-6}/K$ [10] , $\alpha = 0.001cm^{-1}$, $l = 8mm$, $L = 0.038$, $I_0 = 8.31\times10^6 W/m^2$, $K_{NC} = 7.08\times10^{-12}$, $g_0 l_0 = 0.087P_{pump}$. If the thermal lens effect of the TGG crystal is not taken into account, the laser will be in the stable range with the pump power from 44 W to 140 W when the length of L_{34} is 101 mm, and the laser is at the optimal operation point with the pump power of 104 W, which is shown in Fig. 1(a). However, the thermal lens effect of the TGG crystal will not only narrow the stable range with the pump power from 32 W to 112 W but also lowers the threshold and optimal value of the incident pump power, which ultimately limits the output power of the laser, which is shown in Fig. 1(b).

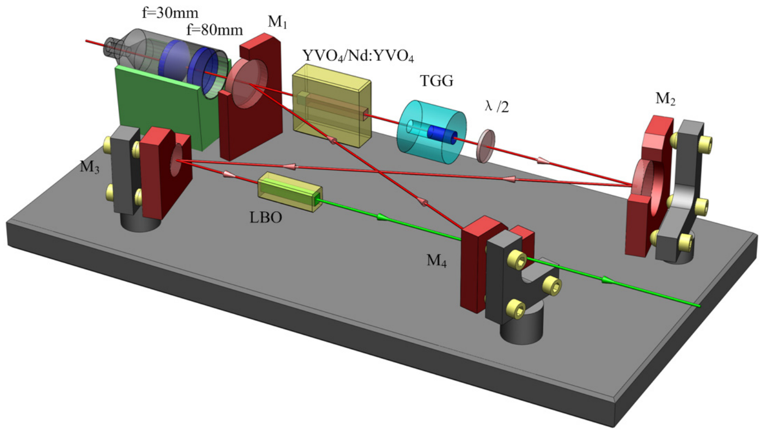

Fig. 3. Schematic diagram of single-end pumped intracavity frequency doubled laser with high output power.

With the thermal lens of the TGG crystal considered, we find that shortening L_{34} can raise the pump power at the optimal operation point of the laser by theoretical calculation. As shown in Fig. 1(c), when L_{34} is shortened from 101 mm to 97 mm, the pump power at the optimal operating point is increased from 70.6 W to 81 W. However, the threshold pump power of the laser is also increased from 32 W to 40 W at the same time. It is demonstrated that shortening the length of the resonator can increase the pump power at the optimal operating point and output power, meanwhile, raise the threshold pump power of the laser in some degree. Furthermore, we calculate the optimal length of L_{34} at different incident pump power, which is shown in Fig. 2. It is clear that the shorter the L_{34} is, the higher the allowable incident pump power is, which provides a guideline to obtain a single-frequency laser with high output power.

3. Experimental setup

The experimental arrangement was shown in Fig. 3. The pump source was a fiber coupled laser diode (LD) (LIMO80-F400-DL888-EX1458), with the output power of 85 W and the central wavelength of 888 nm. The core diameter and numerical aperture (NA) of the coupling fiber were 400 μm and 0.22, respectively. The LD of 888 nm can reduce the waste heat caused by the quantum defect and improve the stability of the laser by the polarization-independent absorption of the pump light in the gain medium [14]. The pump beam was coupled into the resonator and focused at the center of gain medium by a telescope system consisting of two lenses with the focal lengths of 30 mm and 80 mm, respectively. A figure-eight-shaped ring resonator was constructed by four mirrors (M_1-M_4). The input coupler M_1 (R=1500 mm) was a concave-convex lens coated with high reflection (HR) films at 1064 nm (R1064nm>99.7%) and high transmission (HT) films at 888 nm (T_{888nm} >95%); A plane-convex mirror M_2 (R=1500mm) and a plane-concave mirror M_3 (R=-100 mm) were HR coated at 1064 nm (R_{1064nm} >99.7%). The output coupler M_4 (R=-100mm) was also a plane-concave mirror coated with HT films at 532 nm (T_{532nm} >95%) and HR films at 1064 nm (R_{1064nm} > 99.7%). The gain medium was a α-cut composite YVO_4/ Nd:YVO_4 (yttrium vanadate/Nd^{3+}-doped yttrium vanadate) crystal with a length of 23 mm (including an undoped end cap of 3 mm and a 0.8% Nd-doped rod of 20 mm) and a wedge angle of 1.5°. The front end-face of the crystal was coated with AR films for 1064 nm and 888 nm, and the second end-face was coated with AR films only for 1064 nm. The composite gain medium with undoped end cap was employed to relieve the end face

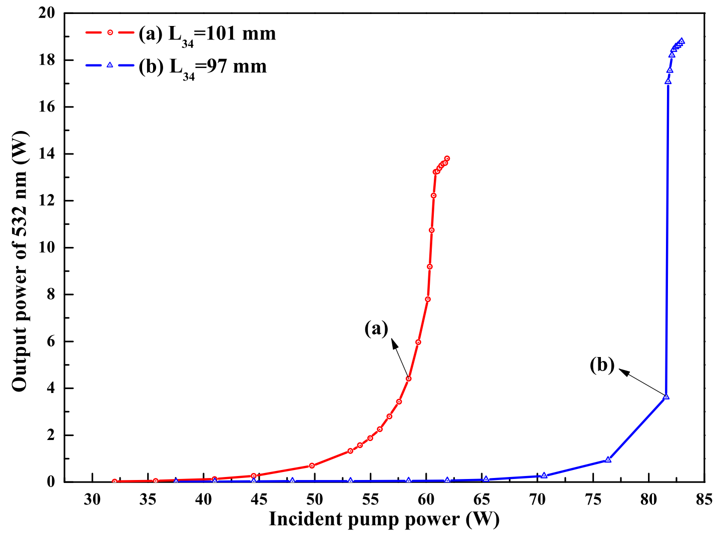

Fig. 4. Output power of 532 nm laser versus the incident pump power.

thermal-induced deformation [5] . The design of the wedged end-facet served as a polarized beam splitter to suppress the σ-polarization oscillation and enhance the superiority of the π-polarization mode in the mode competition [15]. The *c*-axis of gain medium was oriented in the tangential plane in order to realize the mutual astigmatism compensation between the thermal lens of the gain medium and the resonator including four non-plane cavity mirrors with off-axis insllation [8]. To maintain the unidirectional operation of the laser, an optical diode was applied, which consisted of an 8 mm long TGG rod surrounded by a permanent magnet with AR film for 1064 nm and an half-wave plate coated with 1064 nm AR film. The second-harmonic generator was a type-*I* non-critical phase-matching lithium triborate (LBO) crystal with the dimensions of 3 mm$\times$ 3mm$\times$ 20 mm (S_1, S_2 – AR for 1064 nm and 532 nm), which was placed at the beam waist between the mirrors of M_3 and M_4 for higher frequency-doubling efficiency and whose temperature was controlled at 149 °C with a precision of 0.1 °C.

4. Experimental results

When the temperature of the LBO crystal was controlled to the optimal phase-matching temperature of 149 °C, the measured output power of single-frequency 532 nm laser as the function of the incident pump power was shown in Fig. 4. When the L_{34} was 101 mm, the threshold and optimal value of the pump power were 32 W and 61.9 W, respectively, and the maximal output power of 532 nm laser was limited to only 13.8 W. However, when the L_{34} was shortened to 97 mm, the threshold and optimal value of the pump power were 38 W and 82.9 W, respectively, and the maximal output power of single-frequency 532 nm can reach up to 18.7 W with the optical-optical conversion efficiency of 22.6%. The experimental results were in good agreement with the theoretical expectation. It had been proved that the thermal lens effect of TGG crystal was not only existent but also had great influence on laser performance. And we can scale the output power of the single-frequency 532 nm laser by shortening L_{34}. Furthermore, at the optimal operation point of the laser with the pump power of 82.9 W, we deduced the thermal focal length of the TGG crystal (407 mm), which was slightly longer than the theoretical prediction (378 mm) owing to the small differences between the experimental and theoretical parameters of the laser, which provided a method to measure the thermal focal length of the

#232027 - $15.00 USD Received 7 Jan 2015; revised 8 Feb 2015; accepted 9 Feb 2015; published 17 Feb 2015

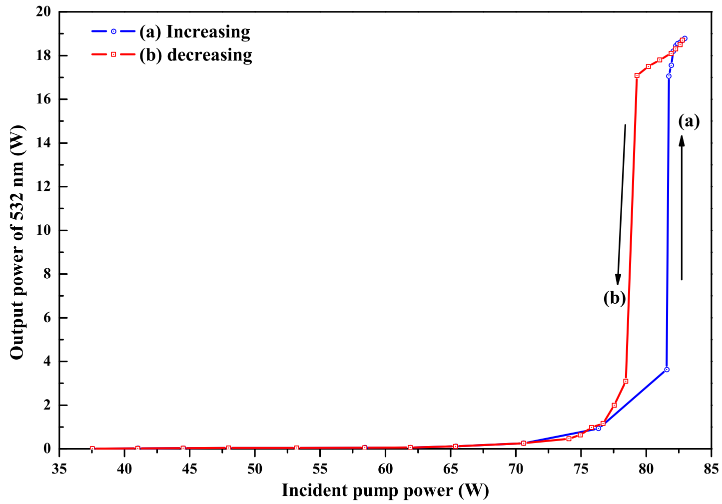

Fig. 5. Output power of the 532 nm laser in the cases of increasing and decreasing the incident pump power.

TGG crystal.

In the cases of increasing and decreasing the incident pump power, a bistability-like phenomenon induced by the thermal lens effect of the TGG crystal was observed since the laser showed different power output characteristic, which is shown in Fig. 5. When the incident pump power was increased from 81.6 W to 81.8 W, the output power jumped from 3.63 W to 17.07 W. However, when the incident pump power was decreased from 79.3 W to 79.1 W, the output power suddenly dropt from 17.09 W to 3.09 W. In our laser resonator, the distance between the gain medium and the TGG crystal was so short that their thermal lens effects were superimposed on each other. The final focal length of thermal lens can be expressed as:

$$\frac{1}{f_{final}} = \frac{1}{f_{Nd:YVO_4}} + \frac{1}{f_{TGG}} \tag{4}$$

At the beginning of increasing the incident pump power, the output power and intracavity power density of the laser was relatively low. At that time, the thermal lens effect of the TGG crystal was not very significant and the final thermal lens effect mainly came from the gain medium. With the increasing of the incident pump power, the intracavity power density continuously increased as well as the output power, which resulted in that the thermal lens effect of the TGG crystal became more and more severe. In the vicinity of the critical point of the output power, the coaction of the thermal lens effect of the gain medium and TGG crystal made the laser rapidly get into the optimal working condition, which manifested itself as the sudden jump of the output power, as the curve (a) shows in Fig. 5. However, when the incident pump power was decreased, even if the thermal lens effect of the gain medium became weaker in some degree, the thermal lens effect of the TGG crystal was still strong enough to keep the laser in the optimal working condition because of the high intracavity power density. With further decreasing of the incident pump power and output power, the thermal lens effect of the TGG crystal became weaker gradually. In the vicinity of the critical point of the output power, the coaction of the thermal lens effect of the gain medium and TGG crystal made the laser rapidly deviate from the optimal work condition, which manifested itself as the sudden drop of the

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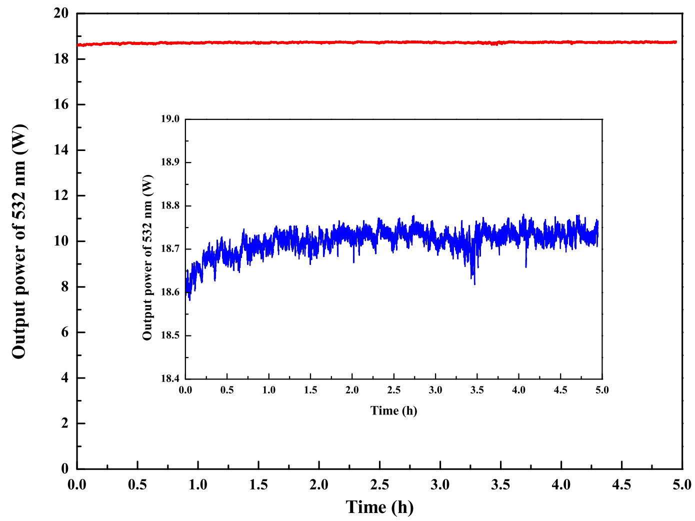

Fig. 6. Long term power stability of 532 nm laser for 5 h.

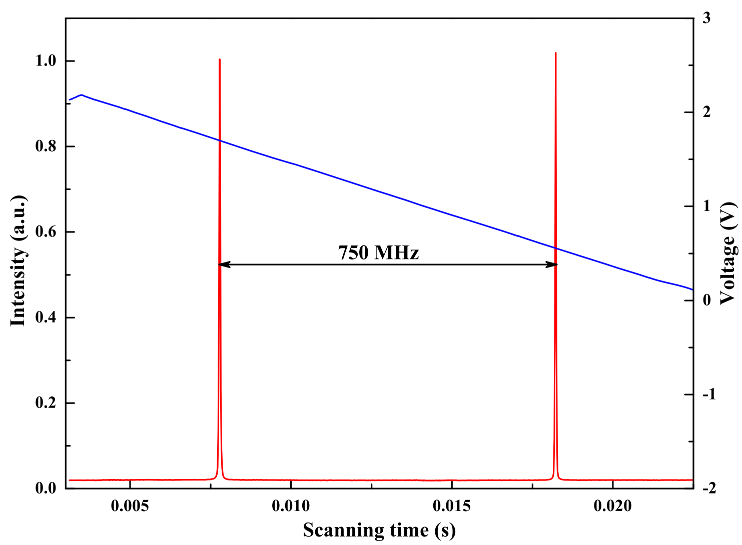

Fig. 7. Longitudinal-mode structure of the laser by scanning the confocal F-P cavity.

output power, as the curve (b) shows in Fig. 5. The bistability phenomenon further proved that the thermal lens effect of the TGG crystal is brought about by the absorption of the intracavity laser radiation rather than others, which was different from that of the gain medium induced by the absorption of the pump light.

When the output power of 532 nm was 18.7 W, we measured the long term stability of the output power for 5 hours, the fluctuation of which is less than ±0.4%, as shown in Fig. 6. A Fabry-Perot cavity with a free spectral range (FSR) of 750 MHz and finesse of 150 was employed to monitor the longitudinal-mode structure of the laser. The resolution of 5 MHz was enough to distinguish the neighbor longitudinal mode of the laser (the separation of the

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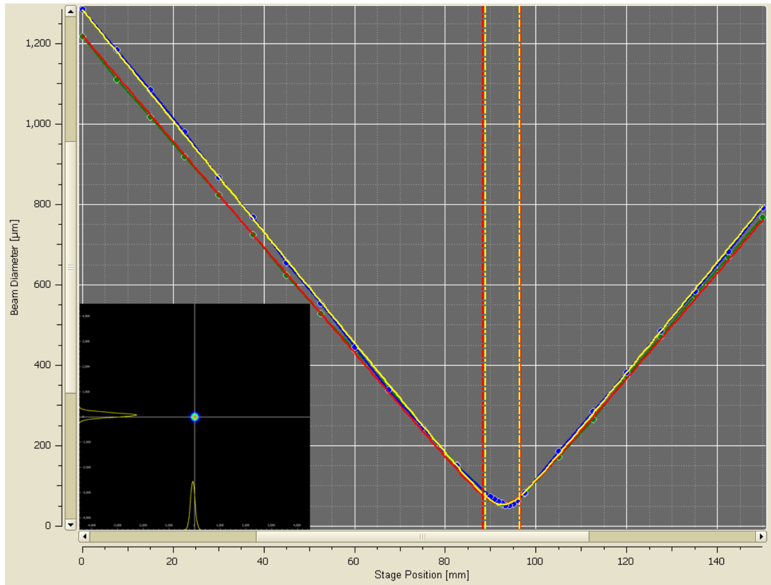

Fig. 8. Measured M^2 values and the spatial beam profile for a 532 nm laser.

longitudinal mode is 625 MHz). The measured result was illustrated in Fig. 7. It indicated that the laser can operate in single-longitudinal-mode, which was attributed to the intracavity nonlinear loss [16]. The beam quality of the laser was measured by a M^2 meter (M2SET-VIS, Thorlabs) and the measured values of M_x^2 and M_y^2 were 1.05 and 1.08, respectively. The measured caustic curve and the corresponding spatial beam profile were shown in Fig. 8 and its inset, respectively.

5. Conclusions

In summary, we have investigated the influence of the thermal lens effect of the TGG crystal in the frequency-doubled laser with high output power and single-frequency operation. Based on the theoretical calculation, we found that the thermal lens effect of TGG crystal was not only existent but can also narrow the stable range of the laser and reduce the threshold and optimal value of the incident pump power, which limited the output power of the single-frequency laser. However, shortening the length of the resonator can optimize the output power in the presence of the thermal lens effect of the TGG crystal. The experimental measurement was in good agreement with the theoretical expectation. In experiment, the output power can be increased from 13.8 W to 18.7 W by shortening the L_{34} from 101 mm to 97 mm. The power stability was better than $\pm 0.4\%$ for 5 hours and the beam quality M^2 was better than 1.08. Meanwhile, we observed and qualitatively analyzed the bistability-like phenomenon of the laser induced by the thermal lens effect of the TGG crystal in the cases of increasing and decreasing the incident pump power, which further proved that the thermal lens effect of the TGG crystal is brought about by the absorption of the intracavity laser radiation. Our work of taking the thermal lens effect of TGG crystal into account can provide a reference in further scaling the output power of a single frequency and frequency doubled lasers with ring resonator.

#232027 - $15.00 USD Received 7 Jan 2015; revised 8 Feb 2015; accepted 9 Feb 2015; published 17 Feb 2015

Acknowledgments

This research was supported in part by the National Natural Science Foundation of China (Grant No. 61405107, 61227902, 61227015), Natural Science Foundation of Shanxi Province (Grant No. 2014021011-3) and Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (Grant No. 2013104).