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High power single-frequency and frequency-doubled laser with active compensation for the thermal lens effect of terbium gallium garnet crystal

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The thermal lens effect of terbium gallium garnet (TGG) crystal in a high power single-frequency laser severely limits the output power and the beam quality of the laser. By inserting a potassium dideuterium phosphate (DKDP) slice with negative thermo-optical coefficient into the laser resonator, the harmful influence of the thermal lens effect of the TGG crystal can be effectively mitigated. Using this method, the stable range of the laser is broadened, the bistability phenomenon of the laser during the process of changing the pump power is completely eliminated, the highest output power of an all-solid-state continuous-wave intracavity-frequency-doubling single-frequency laser at 532 nm is enhanced to 30.2 W, and the beam quality of the laser is significantly improved.

OCIS codes: (140.3580) Lasers, solid-state; (140.3560) Lasers, ring; (140.3570) Lasers, single-mode; (140.6810) Thermal effects.

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All-solid-state single-frequency green lasers with high output power have been widely applied in a lot of science and technology fields, such as holography, interferometry, atom cooling and trapping, generation of deep ultraviolet radiation by second-harmonic generation (SHG), and acting as the pump source of high-power Ti:sapphire lasers. In order to obtain a high-power all-solid-state single-frequency green laser, a ring resonator involving an optical diode (OD) is generally employed. The OD is usually composed of a terbium gallium garnet (TGG) crystal surrounded by a permanent magnet and a half-wave plate. The absorption of laser radiation in the TGG crystal generates a temperature distribution that is nonuniform over its transverse cross section and causes the thermal lens of the TGG crystal. The generated thermal lens not only focuses the fundamental wave (FW) beam and narrows the stable range of the laser but also introduces high-order spatial modes which deteriorate the beam quality severely and limit the output power of the laser through introducing great intracavity losses [1]. We have demonstrated the influence of the thermal lens effect of the TGG crystal on the laser performance and passively adapted to it by shortening the cavity length [2]. However, shortening the cavity length was not able to eliminate the thermal lens effect of the TGG crystal completely. In fact, an obvious bistability phenomenon, which was accompanied by the sharp rise and fall of the output power when the pump power was increased and decreased, had been observed [2]. The abrupt change of the output power causes severe thermal induced stress saltation to the intracavity elements, which will inevitably shorten the service life of the laser. Thus, it is definitely necessary to compensate the thermal lens of the TGG crystal. So far, the compensation for the thermal lens effect of the TGG crystal is mainly focused on the TGG-based Faraday isolator in the gravity wave detection system (GWDS) [1,3,4]. However, the intracavity power intensity of the high-power solid-state laser is much higher than that in GWDS so the thermal lens effect of the TGG crystal of the former is much more severe than that of the latter, which is bound to affect the laser performance severely. There is no literature to deal with the troublesome thermal lens effect of the TGG crystal inside the laser resonator to the best of our knowledge. In this Letter, we present an effective scheme to obtain a stable single-frequency and frequency-doubled laser with high output power. By inserting a potassium dideuterium phosphate (DKDP) slice with negative thermo-optical coefficient into the laser resonator, the thermal lens effect of the TGG crystal in a high-power single-frequency laser can be actively compensated. Using this method, the output power of the laser is significantly promoted, the beam quality of the laser is remarkably improved, and the bistability phenomenon of the laser during the process of changing the pump power is completely eliminated.

In order to actively compensate the thermal lens effect of the TGG crystal and eliminate its influence on the laser performance, a DKDP slice is inserted into the resonator. DKDP crystal is suitable for this task owing to its favorable negative thermo-optical coefficient ($-4.4 \times 10^{-5}/\mathrm{K}$) and absorption coefficient for the 1064 nm laser (0.005/cm). When the distance between the DKDP slice and the TGG crystal is far less than their thermal focal lengths, their effective focal length is given by

$$\frac{1}{f}=\frac{1}{f_{\mathrm{TGG}}}+\frac{1}{f_{\mathrm{DKDP}}}, \tag{1}$$

where f_{TGG}, f_{DKDP} are the thermal focal length of the TGG crystal and the DKDP slice, respectively. As long as f_{TGG} and f_{DKDP} are equal in magnitude but opposite in sign, the thermal lens effect of the TGG crystal can be completely compensated. The thermal focal length of the TGG crystal can be first evaluated according to our experimental conditions. In order to realize the active compensation, the negative thermal lens of the inserted DKDP crystal must exactly follow the variation of the positive thermal lens of the TGG crystal at any FW power. Unfortunately, DKDP crystal is a kind of uniaxial crystal, and its thermal lens is astigmatic in the general case while the thermal lens of the TGG crystal is almost isotropic. Following [4], in order to simultaneously ensure small depolarization and low thermal induced astigmatism in the DKDP slice, the angle between the wave vector of the laser and the optical axis of the DKDP crystal is taken as 30° in our experiment. On this basis, the laser performance is numerically analyzed by the ABCD matrix before and after the DKDP slice is inserted into the resonator, which is depicted in Fig. 1. Before the thermal lens effect of the TGG crystal is compensated, the stable range is much narrower and the pump power at the optimal operation point (OOP) is only 68 W, which is shown in Fig. 1(a). Once the DKDP slice with proper thickness is inserted into the resonator and the thermal lens effect of the TGG crystal is completely compensated, the stable range becomes wider and the pump power at OOP gets raised significantly to 98 W as shown in Fig. 1(b), which is conducive to the promotion of the output power of the laser. It is worth mentioning that the aforesaid calculation is on the premise that the thermal lens effect of the gain medium is taken into account [2].

The experimental setup is shown in Fig. 2. The pump source is a fiber-coupled laser diode with output power of 100 W and central wavelength of 888 nm. A figure-eight-shaped ring resonator is constructed by four mirrors (M_1-M_4). The gain medium is an a-cut 3 mm × 3 mm × (3 + 20) mm composite $\mathrm{YVO_4/Nd{:}YVO_4}$ crystal. To maintain the unidirectional operation of the laser, an optical diode is inserted into the cavity, which consists of a half-wave plate and an 8-mm-long TGG rod installed in the aperture of a permanent magnet. The crystal is a type-I noncritical phase-matching lithium triborate crystal with the dimensions of 3 mm × 3 mm × 22 mm, which is placed at the beam waist between M_3 and M_4 for higher frequency-doubling efficiency. In order to implement the active compensation of the thermal lens effect of the TGG crystal, a DKDP slice is inserted into the resonator, which is mounted in a brass bracket near the TGG crystal.

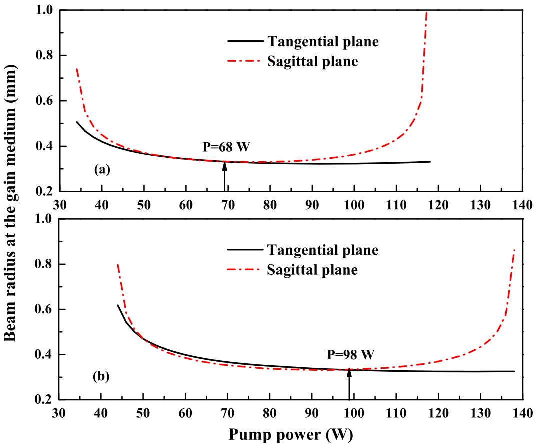


Fig. 1. Stable range of the laser (a) before and (b) after the active compensation of the thermal lens of the TGG crystal.

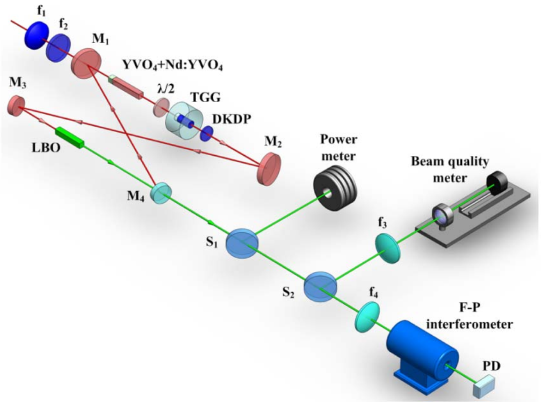


Fig. 2. Experimental setup of active compensation for the thermal lens effect of the TGG crystal. S_1, S_2: beam splitter; f_1, f_2: coupling lens; f_3, f_4: lenses; PD: photodiode detector.

The critical issue with respect to the compensation of the thermal lens effect of the TGG crystal by means of DKDP is the determination of the thickness of the DKDP slice. In our laser system, the DKDP slice was mounted in a brass bracket near the TGG crystal. Since the thickness of the DKDP slice is less than its diameter, the axial heat flow has to be taken into account along with the radial heat flow. Consequently, the formula of the thermal focal length of the DKDP slice has a similar form to that of a rod crystal [5]; meanwhile, it is necessary to add an adjustment factor A in the formula to describe the thermal focal length of the DKDP slice:

$$f_{\mathrm{thermal}}=A\frac{\pi k\omega^2}{Pdn/dt}\frac{1}{1-\mathrm{Exp}(-\alpha l)}, \tag{2}$$

where k and dn/dt are the thermal conductivity coefficient and thermo-optical coefficient of the DKDP crystal, respectively. P is the intracavity FW power of the laser; α and l are the absorption coefficient for FW and the thickness of the DKDP crystal, respectively. ω is the radius of the laser beam in the DKDP crystal. We obtained the value of the adjustment factor A ($\approx$4.2) via the variation of the pump power at OOP in the experiment with three pieces of DKDP slices of different thickness (see Table 1).

Based on the formula in Eq. (2) and the thermal focal length of the TGG rod [2], it can be found that a 1.65-mm-thick DKDP slice can completely compensate the thermal lens effect of the 8-mm-long TGG rod in our laser when the absorption coefficient of the TGG crystal for the FW is 0.002/cm. As a

Table 1. Compensation Result with DKDP Slices of Different Thickness

DKDP Thickness (mm)	$P_{\mathrm{OOP}}{}^{a}$ (W)	Maximum Output Power (W)
uncompensated	71	14.7
0.8	83	20.7
1.2	90	25.2
1.6	95	30.2

[a] The pump power at OOP.

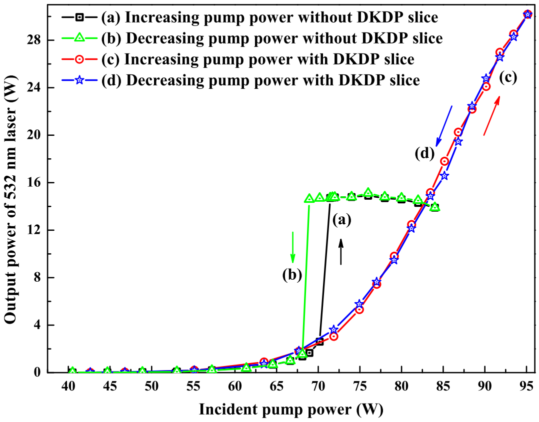


Fig. 3. Output power of 532 nm laser versus pump power before and after the 1.6-mm-thick DKDP slice was inserted into the laser resonator.

consequence, the 1.6-mm-thick DKDP slice was adopted in our experiment.

The output power as a function of the incident pump power is measured before and after the thermal lens of the TGG crystal is actively compensated by the 1.6-mm-thick DKDP slice, which is shown in Fig. 3. Before the active compensation, the pump power at OOP is 71 W and the maximum output power is 14.7 W on the premise of single-frequency operation and perfect beam quality. When the pump power is further increased, the output power does not change notably at first and then begins to decline, accompanied by the appearance of the high order modes. However, after the compensation the pump power at OOP and the maximum output power are promoted to 95 and 30.2 W, respectively, with single-frequency operation and perfect beam quality, which indicates that the experimental results are in good agreement with the theoretical analysis. Therefore, we have obtained an all-solid-state continuous-wave intracavity-frequency-doubling single-frequency 532 nm laser with the highest output power so far. As shown in Fig. 3, the output power characteristic curves after compensation are basically overlapped on each other in the cases of increasing and decreasing the pump power, which demonstrates that the bistability phenomenon of the laser has been completely eliminated so the thermal induced stress saltation in the cavity element has been mitigated to a great extent, which was helpful in prolonging the service life of the laser. Furthermore, it can be found in Fig. 3 that the laser is not saturated at all with pump power of 95 W injected, and the output power can be further promoted if a more powerful pump source is provided.

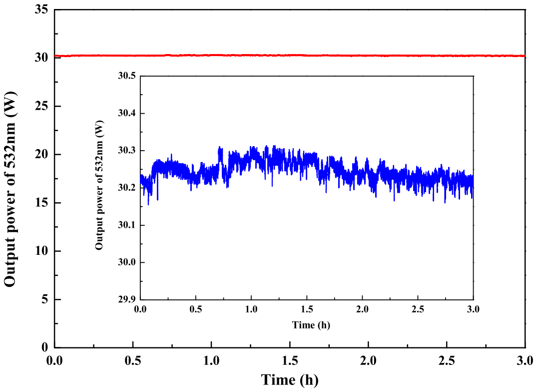
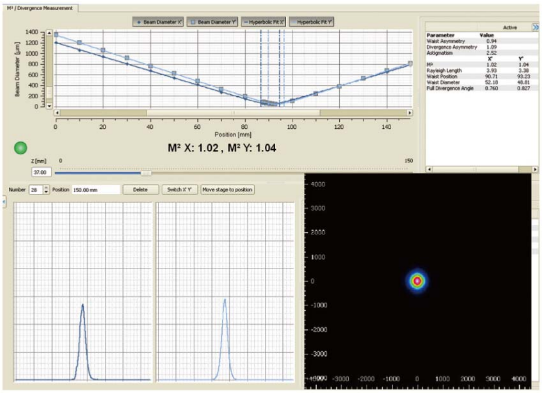


Fig. 4. Long-term power stability of 532 nm laser for 3 h.



M² X: 1.02 , M² Y: 1.04

Z [mm] 37.00

Number 28 Position 150.00 mm

Parameter	Value	
Waist Asymmetry	0.94	
Divergence Asymmetry	1.09	
Astigmatism	2.52	
	X'	Y'
M²	1.02	1.04
Rayleigh Length	3.93	3.38
Waist Position	90.71	93.23
Waist Diameter	52.18	48.81
Full Divergence Angle	0.760	0.827

Fig. 5. Measurement result of the beam quality.

When the output power of 532 nm is 30.2 W, the measured long-term stability of the output power is better than ±0.5%, which is depicted in Fig. 4. The longitudinal-mode structure of the laser was monitored by a Fabry–Perot interferometer with a free spectral range of 750 MHz and finesse of 250, which shows that the laser can operate in single-longitudinal mode stably [6,7]. The beam quality of the laser is measured by a M^2 meter (M2SETVIS, Thorlabs), and the measured values of the beam quality factor in the x and y planes are 1.02 and 1.04, respectively, which is shown in Fig. 5.

In summary, we presented an effective scheme for improving the output power of a single-frequency laser by active compensation of the thermal lens effect of the intracavity TGG crystal. A 1.6-mm-thick DKDP slice was employed to actively compensate the thermal lens in the TGG crystal, by means of which the output power of the laser was significantly promoted and the bistability phenomenon of the laser was completely eliminated. When the incident pump power was 95 W (with 82 W absorbed), a stable singe-frequency 532 nm laser of 30.2 W was obtained, corresponding to an optical-to-optical conversion efficiency of 36.8%, with long-term stability of the output power better than ±0.5% for 3 h and the beam quality factor better than 1.1.

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REFERENCES

1. G. Mueller, R. S. Amin, D. Guagliardo, D. McFeron, R. Lundock, D. H. Reitze, and D. B. Tanner, Class. Quantum Grav. **19**, 1793 (2002).
2. Q. W. Yin, H. D. Lu, and K. C. Peng, Opt. Express **23**, 4981 (2015).
3. E. Khazanov, N. F. Andreev, A. Mal'shakov, O. Palashov, A. K. Poteomkin, A. Sergeev, A. A. Shaykin, V. Zelenogorsky, I. A. Ivanov, R. Amin, G. Mueller, D. B. Tanner, and D. H. Reitze, IEEE J. Quantum Electron. **40**, 1500 (2004).
4. V. Zelenogorsky, O. Palashov, and E. Khazanov, Opt. Commun. **278**, 8 (2007).
5. M. E. Innocenzil, H. T. Yural, C. L. Fincherl, and R. A. Fields, Appl. Phys. Lett. **56**, 1831 (1990).
6. H. D. Lu, J. Su, Y. H. Zheng, and K. C. Peng, Opt. Lett. **39**, 1117 (2014).
7. H. D. Lu and K. C. Peng, J. Quantum Opt. **21**, 171 (2015).