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# Scheme for improving laser stability via feedback control of intracavity nonlinear loss

Pixian Jin, Huadong Lu,* Jing Su, and Kunchi Peng

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Collaborative Innovation Center of Extreme Optics, Institute of Opto-electronics, Shanxi University, Taiyuan 030006, China

*Corresponding author: luhuadong@sxu.edu.cn

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**We present a novel and efficient scheme to enhance the stability of laser output via feedback control to a nonlinear loss deliberately introduced to the laser resonator. By means of the feedback control to the intracavity nonlinear loss of an all-solid-state continuous-wave single-frequency laser with high output power at 1064 nm, its intensity and frequency stabilities are significantly improved. A lithium triborate crystal is deliberately placed inside the laser resonator to be an element of the nonlinear loss, and the temperature of the crystal is feedback controlled by an electronic loop. The control signal is generated by distinguishing the deviation of the output power and used for manipulating the intracavity nonlinear loss to compensate the deviation of the laser power actively. With the feedback-control loop, the intensity and frequency fluctuations of the output laser at 1064 nm are reduced from ±0.59% and 21.82 MHz without the feedback to ±0.26% and 9.84 MHz, respectively.** 

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## 1. INTRODUCTION

All-solid-state continuous-wave (CW) single-frequency lasers pumped by laser diodes (LDs) have played an important role in the fields of science and technology, which is attributed to their favorable features, such as good beam quality, low intensity noise, and high stability. Recently, with the tremendous progress in the fields of quantum information, optical parameter oscillators [1], quantum optics [2,3], and cold atomic physics [4], single-frequency high-power lasers with high stability have attracted more attention from researchers and engineers. In the region of low power, controlling the pump power with an optoelectronic feedback signal affecting the pump current is a feasible way to suppress the power fluctuation of the laser, because the output power can monotonously vary with the pump power. With the pump beam coupled into the laser resonator, the control action of the feedback-control loop directly impacts the performance of the laser. By means of the mentioned method, Lin *et al.* successfully reduced the peak-to-peak laser power fluctuations from ±10% to ±0.5% in 4 h [5]. However, when the laser enters into the region of high power, the severe thermal effect of the gain medium and other intracavity elements breaks the monotonicity between the pump power and the output power, which makes the mentioned method lose efficacy [6]. Electro-optic amplitude modulators (EOAMs) or acousto-optical modulators (AOMs) inserted into the laser output beam could also be used as external power actuators to improve the power stability. The power of the laser beam crossed through the actuators will be stabilized with the actuators controlled by an optoelectronic feedback circuit, accompanied by the loss of a fraction of laser output power. Kim *et al.* reduced the stability of the $Ar^+$ laser from ±0.77% to ±0.20% (based on the rms value) for 12 min by using an AOM, which was used for a direct laser writing system [7]. Lin *et al.* realized a laser power stabilization system with stability of $10^{-5}$ (based on the rms value) order in 1.5 h by means of an AOM [8]. In these laser systems, the output powers were less than 1 W. Meanwhile, when the laser power is higher, the above method is powerless because the low laser damage threshold of the external power actuators limits their applications in the laser with high-power operation. And the external power actuators just act on the output beam of the laser rather than on the laser itself; thus the performance of the laser itself cannot be impacted. For a single-frequency laser with high output power, we have to explore a new method to improve its stability to satisfy the requirements of many experiments.

In this paper, we present a novel and efficient scheme to enhance the stability of fundamental-wave (FW) radiation. First, a nonlinear loss is deliberately introduced to the resonator of an all-solid-state CW single-frequency laser with high output power at 1064 nm, and the output power of the FW 1064 nm laser can be modulated by controlling the nonlinear loss. Then, by means of feedback control to the intracavity nonlinear loss, the power and frequency stabilities of the FW laser are both significantly improved. Lastly, the fluctuations of the laser intensity and frequency are reduced from ±0.59% and 21.82 MHz to ±0.26% and 9.84 MHz, respectively.

## 2. PRINCIPLE ANALYSIS

For a stable FW laser, its gain is equal to the sum of the round-trip intracavity loss ($L$) and the transmission of the output coupler ($t$). When a nonlinear loss ($\varepsilon$) is deliberately introduced to the resonator, the gain of the laser is also decided by $\varepsilon$, and can be expressed as $gl = t + L + \varepsilon$, where $g$ is the gain coefficient per unit length of the laser medium and $l$ is its length. According to previous studies [9–13], intracavity nonlinear loss can efficiently suppress multi-longitudinal-mode (MLM) oscillation and the mode-hopping phenomenon, and the laser can work with single-longitudinal-mode (SLM) operation forever. Furthermore, the intensity noise of the FW and second-harmonic wave (SHW) can also be manipulated by controlling the intracavity nonlinear loss [14]. According to Refs. [9,11], the intracavity nonlinear loss is equal to the conversion efficiency of the nonlinear crystal, and $\varepsilon = \eta I$, where $\eta$ is the nonlinear conversion factor and $I$ is the intracavity FW intensity. In this case, once the laser resonator is designed and the transmission of the output coupler ($t$) is chosen, the intracavity FW intensity is decided by the nonlinear conversion factor ($\eta$) [13] and can be expressed as

$$I = \frac{\sqrt{(t + L - I_0\eta)^2 + 4\eta I_0 g_0 l} - (t + L + I_0\eta)}{2\eta}, \quad (1)$$

where $I_0$ is the saturation intensity, $g_0$ is the small signal gain factor, $g_0 l = 0.07P_{\mathrm{in}}$, and $P_{\mathrm{in}}$ is the pump power. The output powers of the FW and SHW are given by

$$P_f = AtI, \quad (2)$$

$$P_s = \varepsilon AI = \eta AI^2, \quad (3)$$

where $A$ is the average transverse cross section of the laser beam in the gain medium. Substituting Eqs. (1)–(3), we can obtain

$$P_f = At\frac{\sqrt{(t + L - I_0\eta)^2 + 4\eta I_0 g_0 l} - (t + L + I_0\eta)}{2\eta}, \quad (4)$$

$$P_s = A\frac{\left[\sqrt{(t + L - I_0\eta)^2 + 4\eta I_0 g_0 l} - (t + L + I_0\eta)\right]^2}{4\eta}. \quad (5)$$

From Eqs. (4) and (5), it is clear that the output powers $P_f$ and $P_s$ are both modulated by $\eta$; then $P_f$ and $P_s$ can be stabilized by controlling the intracavity nonlinear loss. There are many methods to manipulate the intracavity nonlinear loss, such as controlling the phase-matching temperature or the phase-matching angle of the nonlinear crystal. In our experiment, the intracavity nonlinear loss is manipulated by controlling the phase-matching temperature of the nonlinear lithium triborate (LBO) crystal. When the LBO crystal acts as the intracavity nonlinear element, the nonlinear conversion factor $\eta$ is equal to [15]

$$\eta = K \sin c^2\left[\left(\frac{2\pi}{\lambda_f}\frac{dn_z}{dT} - \frac{\pi}{\lambda_s}\frac{dn_y}{dT}\right)\Delta T l_1\right], \quad (6)$$

where $\Delta T = T - T_0$, $T$ is the temperature of the LBO crystal, $T_0$ is its optimal phase-matching temperature, $K$ is a constant, $\lambda_f$ and $\lambda_s$ are the wavelengths of the FW and SHW, respectively, $dn_z/dT = (-6.3 + 2.1\lambda_f) \times 10^{-6}$, $dn_y/dT = -13.6 \times 10^{-6}$, and $l_1$ is the length of the nonlinear crystal. The theoretical predictions of the normalized output powers of the laser versus $T$ are shown in Figs. 1(a) and 1(b). It can be known that the output power of the 1064 nm laser varies nonlinearly with the temperature of the LBO crystal and the temperature is a slow variable relatively. Thus, a suitable lock point in the laser system should be chosen carefully to achieve the best stabilization effect. The appropriate lock point should fulfill the following conditions: (1) the laser should always remain in SLM operation, (2) the output power of the laser should change monotonously with the temperature of the LBO crystal, and (3) the output power of the laser should respond as fast as possible to the variation of the temperature of the nonlinear crystal.

By taking $d\eta/dT$, the derivative of $\eta$ with respect to the temperature of the LBO crystal is expressed as

$$\frac{d\eta}{dT} = -\frac{2K[\Delta k l_1 \cos(\Delta k l_1) - \sin(\Delta k l_1)]\sin(\Delta k l_1)}{(\Delta k l_1)^2 \Delta T}, \quad (7)$$

where $\Delta k = (\frac{2\pi}{\lambda_f}\frac{dn_z}{dT} - \frac{\pi}{\lambda_s}\frac{dn_y}{dT})\Delta T$. The $d\eta/dT$ versus $T$ is shown in Fig. 1(c). With $d\eta/dT = 0$, it is obtained that the optimal phase-matching temperature of the LBO crystal is 149.2°C (A) and there are two monotonous sectors around the optimal phase-matching temperature: $\mathrm{T}_1 \to [146.2, 149.2]$

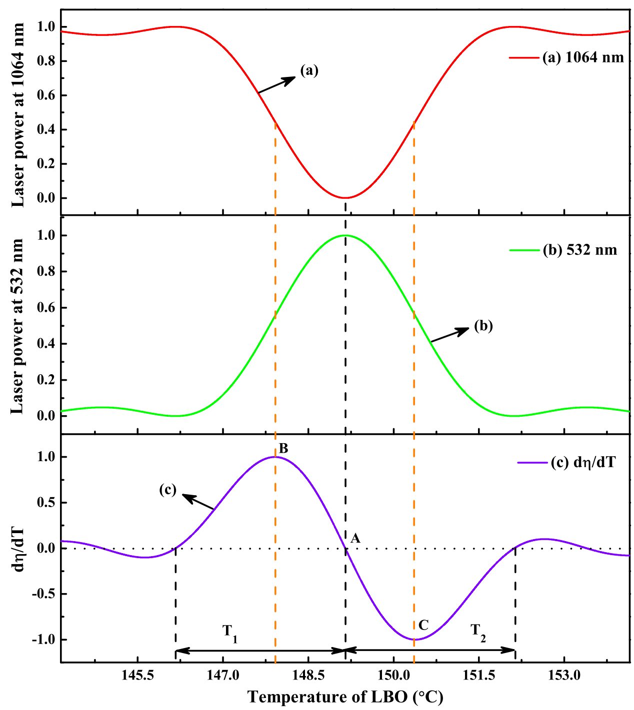


**Fig. 1.** Theoretical predictions of the normalized output powers of the laser and $d\eta/dT$ versus the temperature of LBO. (a) Output power of 1064 nm laser. (b) Output power of 532 nm laser. (c) $d\eta/dT$.

and $T_2 \rightarrow [149.2, 152.2]$. When the temperature of LBO crystal is within the range of 146.2°C to 149.2°C, the nonlinear loss is monotone increasing, while the output power of the FW laser is monotone decreasing with the increase of the temperature of LBO, and it is the opposite when the temperature of LBO crystal is in the other monotonous zone. According to the physical condition of SLM operation of the laser, however, the temperature of LBO crystal should be limited within ±2°C around the optimal phase-matching temperature [11]. At that time, the upconversion efficiency is higher than 1.13%. So the allowable temperature range of LBO crystal is limited within 147.2°C–149.2°C (or 149.2°C–151.2°C). From Fig. 1, we also find that the largest absolute of the $d\eta/dT$ is at the temperature point of 147.9°C or 150.4°C (B and C), where the response of the output power of the FW is fastest to the variation of the LBO crystal temperature. In short, the operation temperature of LBO crystal near 147.9°C (or 150.4°C) should be the optimal choice to achieve the best performance of the stabilization of the fundamental-wave output power, and the controllable range of the output power of the FW is limited by the allowable temperature range of the LBO crystal, 147.2°C–149.2°C (or 149.2°C–151.2°C).

## 3. EXPERIMENTAL SETUP

The experimental setup for improving the laser stability via feedback control of intracavity nonlinear loss is shown in Fig. 2. The configuration of the laser source used for this experiment has been presented in our previous publications [11,13]. A CW fiber coupled LD with maximum output power of 80 W and center wavelength of 888 nm [16] (LIMO80-F400-DL888EX1458, LIMO Lissotschenko Mikrooptik GmbH) is used as the pump source. The LD pumped beam is coupled into the gain medium by using a telescope system composed of two lenses $f_1$ and $f_2$. A figure-eight-shaped ring resonator is constructed by four mirrors ($M_1$_$M_4$). The gain medium is an $\alpha$-cut composite $YVO_4$/Nd:$YVO_4$ (yttrium vanadate/$Nd^{3+}$-doped yttrium vanadate) rod with a length of 23 mm (including undoped end cap of 3 mm and 0.8% Nd-doped part of 20 mm) and a wedge end facet of $\alpha = 1.5°$ [17]. An optical diode consisting of a half-wave plate (HWP) and a terbium gallium garnet (TGG) crystal surrounded by a permanent

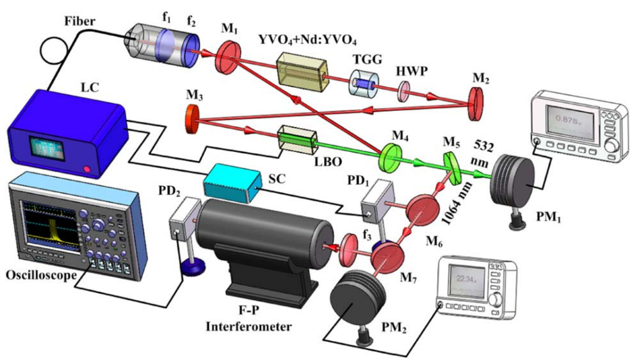


**Fig. 2.** Experimental setup of the single-frequency laser with power stabilization system for fundamental wave. HWP, half-wave plate; $PM_1$ and $PM_2$, power meters; $PD_1$ and $PD_2$, photodetectors; LC, laser controller; SC, servo controller.

magnet is used to ensure the laser's unidirectional operation. In order to achieve stable SLM operation and improve the stability of the FW radiation, a nonlinear LBO crystal with type-I noncritical phase matching is deliberately inserted into the resonator. The intracavity nonlinear loss can be manipulated by controlling the temperature of the LBO crystal with accuracy of ±0.005°C by a laser controller (LC, DSP-I Laser System Controller, YuGuang Co., Ltd.). The output coupler ($M_4$) of the laser is coated with partial transmission film at 1064 nm (with the transmission of $t$) and high-transmission film at 532 nm ($T_{532\,nm} > 95\%$). When the intracavity FW laser traverses the LBO crystal, a fraction of the FW laser is converted to the SHW, which directly leaks from the $M_4$ along with the generated FW laser. The output FW and SHW lasers are first separated by a dichroic mirror $M_5$ coated with the films of high transmission at 532 nm and high reflection at 1064 nm. The reflected 1064 nm laser is applied to generate the feedback signal and monitor the stability of the 1064 nm laser.

In order to stabilize the output power of the 1064 nm laser by feedback manipulating the intracavity nonlinear loss, an optoelectronic negative feedback-control loop is added to the laser system. Its function is to distinguish the power deviation and generate the control signal. The schematic of the feedback-control loop is shown in Fig. 3. A small part of the 1064 nm laser reflected by $M_6$ is injected into a photodiode (ETX-500, JDSU corporation) mounted on a photodetector ($PD_1$). The detected photocurrent is converted to a voltage signal by a transimpedance amplifier (TIA). Comparing (by AD620) the converted voltage signal with low-noise reference voltage supplied by a high-precision 5 V reference (Analog Devices AD586) and a potentiometer in the servo controller (SC), the required error signal is obtained. The generated error signal is amplified and integrated to obtain the control signal. Finally, the produced control signal is introduced into the LC and superposed with the temperature setting signal of the temperature control loop of the LBO crystal to adjust the temperature of the LBO crystal. Once the output power of the FW laser deviates from the reference power value, which corresponds to a reference voltage value, the SC will begin to work and the setting value of the temperature control loop of the LBO crystal will be changed. With the variation of the setting temperature of the LBO crystal, the actual temperature of the LBO crystal will be changed. Eventually, the intracavity nonlinear loss is adjusted and the output power of the FW laser is stabilized.

After the optimal operation temperature of LBO crystal is ascertained according to Section 2, the reference power value of the 1064 nm laser is determined (see Fig. 1), which corresponds to a reference voltage in SC. In the experiment, the output power of the 1064 nm laser at the temperature 150.4°C of LBO

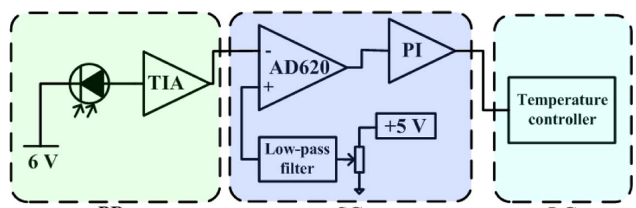


**Fig. 3.** Schematic of the feedback-control loop.

crystal is chosen as the reference power value based on the above theoretical analysis, where the output power of the 1064 nm laser is 23.2 W. According to the actual output power value of the 1064 nm laser and the detected ratio of 0.167 V/W between the signal from $PD_1$ and the output power of the 1064 nm laser, the suitable reference voltage is set to 3.86 V by adjusting the potentiometer in SC. The rise time of the step response of the temperature controller in the laser system is 5.9 s. To make the SC match with the temperature controller, the time constant of 5.9 s of the proportional-integral (PI) control circuit is designed and its proportionality coefficient of 0.147 is designed, which is needed for the error signal generated by the AD620 to superpose with the temperature setting signal. In that case, the rise time of the stabilization system is 5.9 s and the laser power fluctuation in the frequency range lower than 170 mHz can be suppressed effectively by feedback controlling the temperature of the LBO crystal.

To assess the properties of the laser with the feedback-control loop, the laser output powers are measured and the longitudinal-mode structure of the laser is monitored. The leaked 532 nm laser from $M_5$ is recorded by a power meter ($PM_1$, LabMax-TOP, Coherent). A small part of the 1064 nm laser reflected by $M_7$ is injected into a Fabry–Perot (F-P) interferometer with a free spectral range (FSR) of 750 MHz and finesse of 100 (F-P-100, Yuguang Co., Ltd.), respectively, to monitor the longitudinal-mode structure of the laser. The transmitted signal of the F-P interferometer is detected by another photodetector ($PD_2$) and recorded by a digital storage oscilloscope (Tektronix DPO 4104). The rest of the 1064 nm laser is recorded by another power meter ($PM_2$, LabMax-TOP, Coherent).

## 4. EXPERIMENTAL RESULTS

When the transmission of the output coupler $M_4$ is 19% and the temperature of the LBO crystal is controlled to the optimal phase-matching temperature of 149.2°C, the threshold pump power is 29.3 W and the maximal output power of the single-frequency 1064 nm laser is 22.7 W under the pump power of 74.0 W, while the output power of the laser at 532 nm is 1.27 W. The optical–optical conversion efficiency is 32.4%. According to the above analysis, the temperature of the nonlinear LBO crystal is detuned to 150.4°C and the reference voltage in the SC is set to 3.86 V. The power fluctuation of the fundamental-wave laser is measured in 4 h with two phases: free-running phase and controlled phase, which is shown in Fig. 4. When the laser is free-running, the stability of the output power of the 1064 nm laser is ±0.59% in 2 h. However, when the SC begins to work, the laser is controlled and the power fluctuation of the fundamental-wave 1064 nm laser is reduced to ±0.26% in 2 h. The obtained power fluctuation of ±0.26% (peak-to-peak value) is less than that of the commercially available lasers, such as Verdi V lasers produced by Coherent, which have power fluctuation of ±1% for 2 h [18]. The comparison shows that the presented method of feedback control to the intracavity nonlinear loss in this paper can remarkably enhance the stability of the FW laser. In the process of the experiment, the longitudinal-mode structure of the laser is always monitored by the F-P interferometer, and the frequency stability of the laser is recorded at both phases, which is shown in Fig. 5. In order to avoid the influence of the ambient mechanical vibration on the measured results of the frequency drift as much as possible, the measurement interval of 1 min is chosen at both phases. It is clear that the frequency drift can be reduced to 9.84 MHz from 21.82 MHz in 1 min when the laser turns to the controlled phase from the free-running phase. The decrease of the frequency drift results from the improvement of the power stability. When the laser works in the controlled phase, the power of the laser can be stabilized by controlling the intracavity nonlinear loss. In that case, the variation of the laser resonator length due to the fluctuation of the environment temperature is suppressed and the frequency fluctuation is also reduced. Compared to feedback control of

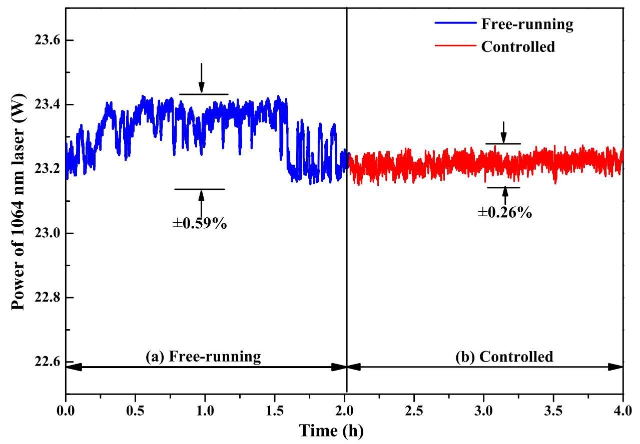


**Fig. 4.** Power stability of 1064 nm laser in 4 h with two phases: (a) free-running phase and (b) controlled phase.

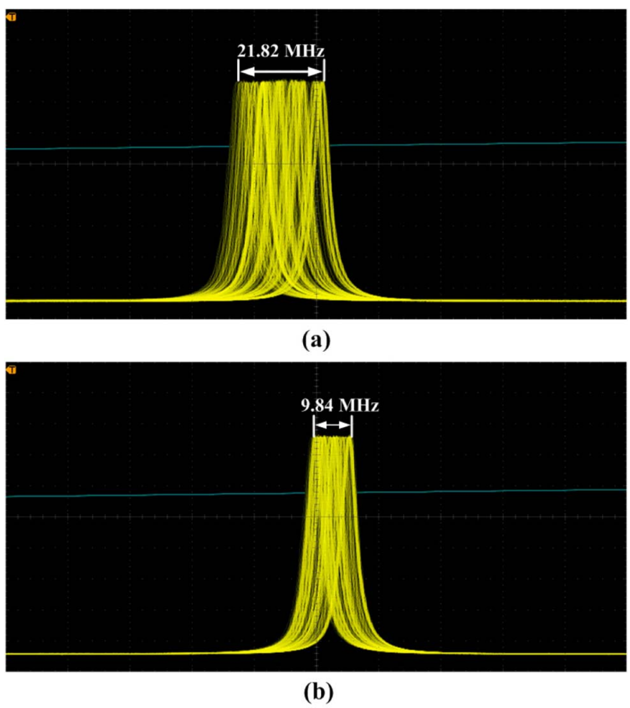


**Fig. 5.** Frequency drift of 1064 nm laser in 1 min at two phases: (a) free-running phase and (b) controlled phase.

the pump power, the presented method is suitable for high-power single-frequency lasers and cannot be limited by the monotonicity between the pump power and the output power, which is necessary for the conventional stabilization methods via feedback control to the pump current of the laser.

## 5. CONCLUSION

In summary, a novel and efficient scheme to enhance the stability of the laser output via feedback control to a nonlinear loss deliberately introduced to the laser resonator has been presented, and the stability improvement of a single-frequency FW 1064 nm laser has been effectively implemented. The manipulation of the intracavity nonlinear loss in our experiment was achieved by controlling the temperature of the intracavity nonlinear LBO crystal. The experiment results showed that the power fluctuation of the fundamental-wave 1064 nm laser was reduced to $\pm 0.26\%$ in 2 h when the laser was working in the controlled phase, which was obviously lower than that of $\pm 0.59\%$ when the laser was working in the free-running phase. Simultaneously, the frequency drift of the FW 1064 nm laser was suppressed from 21.82 to 9.84 MHz in 1 min when the laser turned to the controlled phase from the free-running phase. The research illustrates that not only the output power stability but also the frequency stability of the FW 1064 nm laser can be improved by feedback manipulating the intracavity nonlinear loss. The obtained stable single-frequency 1064 nm laser with high output power can be well used in atomic-cooling physics, optical parameter oscillators, etc. If only changing the transmission of the output coupler of the laser, a single-frequency SHW laser with main output wavelength of 532 nm will be achieved. The output powers of the FW and SHW are also related to the intracavity nonlinear loss. In this case, the presented stabilization scheme of feedback control of intracavity nonlinear loss can also be used to stabilize the output power of the single-frequency 532 nm laser with high-power operation.

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