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PULSE FLUCTUATIONS CAUSED BY THE THERMAL LENS EFFECT IN A PASSIVELY Q-SWITCHED LASER SYSTEM

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Abstract

We study theoretically and experimentally pulse fluctuations in a passively Q-switched laser caused by the thermal lens effect and design a special thermally insensitive cavity for an end-pumped passively Q-switched laser system with a composite crystal. We show experimentally that using a suitable cavity and maintaining the laser-system operation in the fundamental mode reduce the pulse fluctuations effectively. Under a pump power of 8 W, relative fluctuations of the pulse width and the repetition rate of this system are 2.3% and 3.5%, respectively.

Keywords: laser resonators, laser stabilization, lasers, Q-switched lasers.

1. Introduction

Q-switching technology is a key technology for obtaining high-peak power lasers. Q-switched laser systems have already been used in many fields, including biomedicine, manufacturing industries, and scientific research. When compared with actively Q-switched laser systems, passively Q-switched laser systems that use saturable absorbers are more compact, robust, and lower in cost. However, the latter laser systems have a significant disadvantage due to the instability of their pulse widths and repetition rates [1, 2], which thus limits their applications. The pulse width and the repetition rate of a passively Q-switched laser both depend on the light intensity in the cavity [3]. Uncontrollable fluctuations in the pump power and the temperature of the crystals will thus lead to output-pulse instabilities.

Many methods for reduction of time jitter have previously been reported, including increased gain modulation [4] or loss modulation [5], and use of synchronized Q-switching [6] or periodically modulated pumping [7]. Nevertheless, only a few researchers have focused on the pulse fluctuations caused by the thermal lens effect [8], and most of the methods for reduction of the time jitter are based on active

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modulation, which makes the system more complex and expensive. The use of a passive modulation method to reduce the fluctuations caused by unstable temperatures is therefore an interesting research topic.

In addition to pump-power fluctuations, temperature fluctuations are another main reason for the instability of the output pulses. Bonding of a nondoped crystal at the end face of the gain medium or saturable absorber can accelerate heat transfer and reduce the thermal lens effect, and this method has already been used in different types of laser systems [9–11]. However, because of the relatively slow heat transfer of these crystals and the limitations of the temperature control processes, the thermal lens effect cannot be avoided completely, especially in laser diode (LD) end-pumped systems. In view of these facts, a special thermally insensitive resonant cavity should be used to reduce the influence of the thermal lens effect. If the beam quality in the thermally insensitive cavity hardly changes with temperature fluctuations, the light intensity and output pulses become more stable.

In this paper, we present a theoretical analysis of pulse fluctuations caused by the thermal lens effect in a passively Q-switched laser system and carry out some experiments to verify the numerical simulation. Using a Nd:YAG/Cr^{4+}:YAG/YAG composite crystal and a special thermally insensitive cavity, we obtain stable laser output pulses. Under a pump power of 8 W, relative fluctuations of the pulse width and the repetition rate in this system are 2.3% and 3.5%, respectively. The experimental results show that use of a suitable cavity structure and maintaining laser-system operation in the fundamental mode can reduce the pulse fluctuations effectively.

2. Analysis and Design

The mechanism of the output pulse instability caused by the thermal lens effect is shown in Fig. 1. When the focal length of the thermal lens changes from f_1 to f_2, the diameter of the light spot on the saturable absorber changes from ω_1 to ω_2. Assuming that the energy of the fundamental laser mode remains at a constant value under a specific pump power without any fluctuations, the intensity will thus increase when the size of the light spot on the saturable absorber is reduced, and vice versa. With different changes in the light intensity, the system needs correspondingly different times to bleach the saturable absorber, which would subsequently lead to different pulse widths and repetition rates.

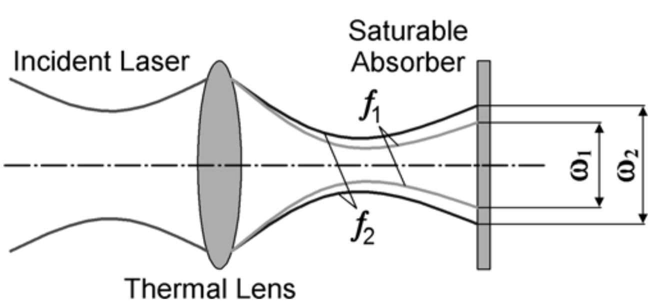

Fig. 1. Relationship between the focal length of thermal lens f_1 (gray curve) and f_2 (black curve) and the diameter of light spot on the saturable absorber.

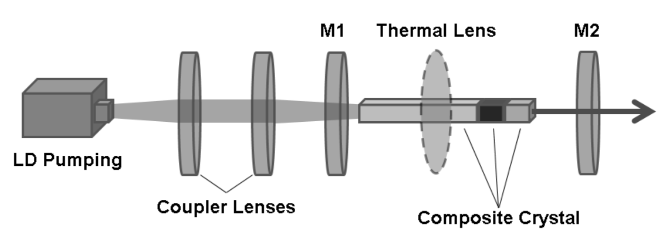

Fig. 2. Experimental set up of the laser system.

In addition, the multimode operation increases the instability of the output pulses in a passively Q-switched laser system. An experimental laser system, shown in Fig. 2, is set up to verify this analysis.

The pump source is a 20-W fiber-coupled laser diode operating at 808 nm (the fiber core diameter is 300 μm and its numerical aperture is 0.22). The coupler lenses (1:1 magnification) are used to reimage the pump beam into a composite Nd:YAG/Cr^{4+}:YAG/YAG crystal. The linear cavity was composed of two plane mirrors, M1 and M2; here, M1 has a high-reflectivity (HR) coating at 1,064 nm (reflectivity $R > 99.6\%$), and the output coupler M2 has a partially reflective (PR) coating at 1,064 nm ($R = 90\%$). The dimensions of the composite crystal are $4{\times}4{\times}12$ mm^3. The lengths of the Nd:YAG, Cr^{4+}:YAG, and YAG crystals are 8, 2, and 2 mm, respectively. The Nd:YAG crystal is doped with 1.0 at.% of Nd^{3+} ions, and the initial transmission of the Cr^{4+}:YAG crystal is 90%. The complete composite crystal was wrapped in indium foil and mounted in water-cooled copper blocks. The cavity length is 48 mm. The distances from M1 to the composite crystal and from the composite crystal to M2 are both 18 mm.

The output of this laser system changes from the fundamental mode to the multimode regime with increasing pump power, and the amplitude fluctuations of the laser output become significant when the system changes to multimode operation, as shown in Fig. 3.

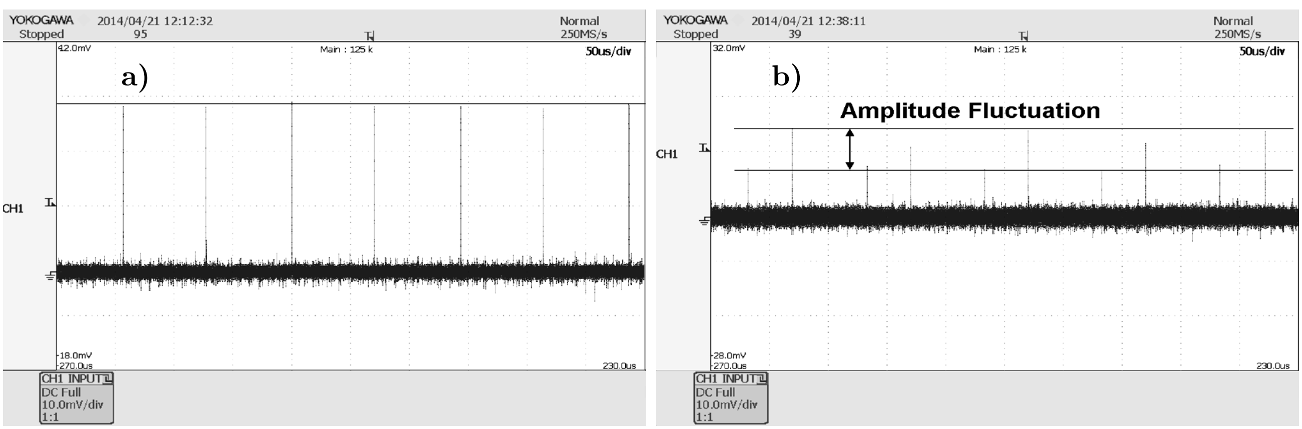

Fig. 3. Amplitude fluctuations of the laser system under different pump powers: low-pump power (a) and high-pump power (b).

For further investigation of the pulse fluctuations caused by the thermal lens effect in passively Q-switched laser systems, we employed the rate equation for numerical simulation of the pulse width and repetition rate.

The intracavity photon density is assumed to have a Gaussian spatial distribution during the entire pulse formatting process, and the laser system is also assumed to be operating in the fundamental mode (i.e., the TEM_{00} mode). The intracavity photon density $\varphi(r,t)$ and photon densities at the positions of the gain medium $\varphi_g(r,t)$ and the saturable absorber $\varphi_s(r,t)$ can be expressed as follows [8]:

$$\varphi(r,t) = \varphi(0,t)\exp(-2r^2/\omega_l^2), \quad \varphi_g(r,t) = \varphi_g(0,t)\exp(-2r^2/\omega_g^2), \quad \varphi_s(r,t) = \varphi_s(0,t)\exp(-2r^2/\omega_s^2),$$

where r is the radial coordinate, $\varphi(0,t)$ is the average photon density on the laser axis Z, ω_l is the average radius of the TEM_{00} mode, $\varphi_g(0,t)$ and $\varphi_s(0,t)$ are the photon densities on the laser axis at the positions of the gain medium and the saturable absorber, and ω_g and ω_s are the TEM_{00} mode radii at these two positions, respectively.

We assume that the value $\int\limits_0^\infty \frac{d\varphi_(r,t)}{dt} 2\pi r\,dr$ can be unchanged at any point on the Z axis. Also, while analyzing a passively Q-switched laser radiation process, the spatial variations in the population-inversion density of the gain medium and in the ground-state population density of the saturable absorber should be taken into account. In view of these facts, the rate equations for the passively Q-switched laser system read [8]

$$\int_0^\infty \frac{d\varphi(r,t)}{dt} 2\pi r\, dr = \int_0^\infty \frac{1}{t_r}\big\{2\sigma n(r,t) l\varphi_g(r,t) - 2\sigma_g n_{s1}(r,t) l\varphi_s(r,t) - 2\sigma_e\big[n_{s0} - n_{s1}(r,t)\big] l\varphi_s(r,t) - \ln(1/R)\varphi_s(r,t) - L\varphi_(r,t)\big\} 2\pi r\, dr, \quad (1)$$

$$\frac{dn(r,t)}{dt} = R_{\rm in}(r) - \sigma c n(r,t)\varphi_g(r,t) - \frac{n(r,t)}{\tau}, \quad (2)$$

$$\frac{dn_{s1}(r,t)}{dt} = \frac{n_{s0} - n_{s1}(r,t)}{\tau_s} - \sigma_g c n_{s1}(r,t)\varphi_s(r,t), \quad (3)$$

where we used the following notation:

σ, n_g, l, and τ are the stimulated emission cross-section, refractive index, length, and stimulated radiation lifetime of the gain medium; σ_s, σ_e, l_s, τ_s, $n_{s1}(r,t)$, n_{s0}, and n_s are the ground-state absorption cross-section, excited-state absorption cross-section, length, excited-state lifetime, ground-state density, total population density, and refractive index of the saturable absorber; $n(r,t)$ is the average population-inversion density; $t_r = 2l_e/c$ is the round trip time with l_e being the optical length of the cavity and c the velocity of light in vacuum; R is the reflectivity of the output mirror; L is the intrinsic loss.

Then the pump rate $R_{\rm in}(r)$ reads

$$R_{\rm in}(r) = P_{\rm in}\left[1 - \frac{\exp(-\alpha l)\exp(-2r^2/\omega_p^2)}{h\nu_p \pi \omega_p^2 l}\right], \quad (4)$$

where ω_p is the radius of the pump beam in the gain medium, α is the absorption coefficient of the gain medium, h is the Planck constant, ν_p is the frequency of the pump laser, and and $P_{\rm in}$ is the pump power.

The pulse width and repetition rate of the laser system are shown in Fig. 2; they were calculated using Eqs. (1)-(3) combined with mathematical software. The values of ω_l, ω_g, and ω_s are determined by the cavity configuration and can be calculated, in view of the ABCD matrix theory. The other parameters required for the numerical calculations are shown in Table 1.

Table 1. Parameters for the Calculations [3, 8].

Parameter	Value	Parameter	Value
σ	$2.8 \cdot 10^{-19}$ cm^2	n_g	1.82
σ_s	$7 \cdot 10^{-18}$ cm^2	n_s	1.8
σ_e	$2 \cdot 10^{-18}$ cm^2	ω_p	150 μm
n_{s0}	8.5	R	90%
τ_s	3.4 μs	l	8 mm
L	0.05	l_s	2 mm

We assumed the focal length of the thermal lens to be 130 mm under a specified pump power, with fluctuations of $\pm$20 mm caused by the temperature instability. The results of numerical simulation for a single pulse and a pulse sequence are shown in Figs. 4 and 5. According to the calculations, the pulse width is approximately 35.07 ns with a fluctuation of $\pm$1.58 ns, while the repetition rates barely change and maintain a value of 26.36 kHz.

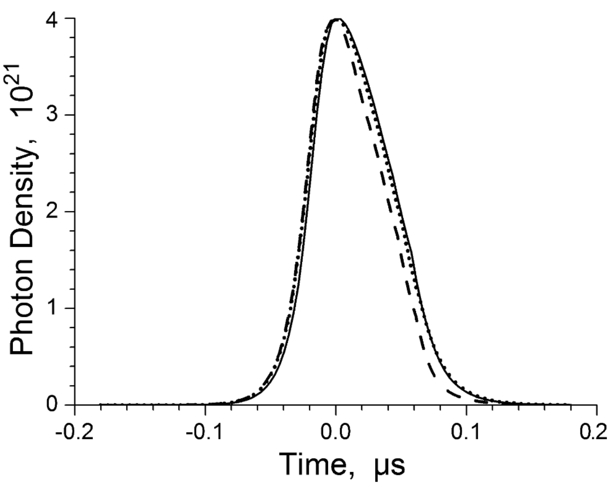

Fig. 4. Intracavity photon density on a time scale of the laser-pulse width at f = 110 mm (solid curve), f = 130 mm (dotted curve), and f = 150 mm (dashed curve).

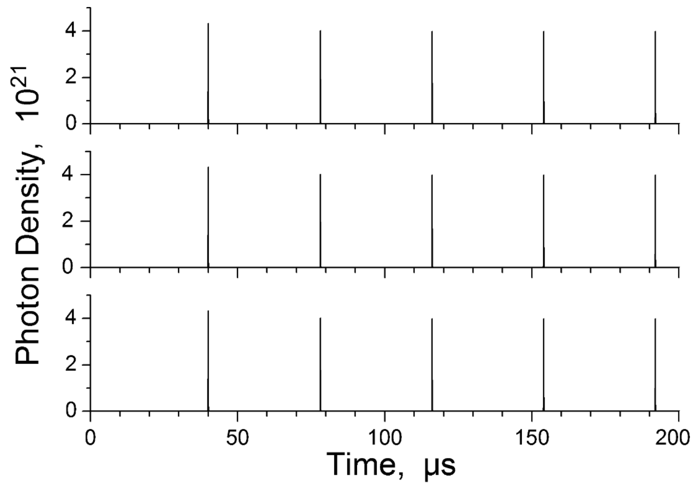

Fig. 5. Intracavity photon density as a function of time at f = 110 mm (top), f = 130 mm (middle), and f = 150 mm (bottom).

We calculate relative fluctuations of the pulse width δ_a and repetition rate δ_T from the following equations:

$$\delta_a = \frac{Pw_{\max} - Pw_{\min}}{P_{\text{average}}} \cdot 100\%, \qquad \delta_T = \frac{T_{\max} - T_{\min}}{T_{\text{average}}} \cdot 100\% \tag{5}$$

and obtain $\delta_a = 4.53\%$ and $\delta_T = 0.08\%$. In Eq. (5), we used the following notation: $Pw_{\max}$ and $Pw_{\min}$ are the maximum and minimum pulse widths, $T_{\max}$ and $T_{\min}$ are the maximum and minimum repetition rates, and P_{average} and T_{average} are the average pulse width and the average repetition rate, respectively.

Compared with the influence of the pump power fluctuations, the influence of the temperature fluctuations is not obvious, especially at the repetition rate used for the laser output.

Based on the analysis above, we relate the fluctuations in the pulse width and repetition rate caused by the thermal lens effect to the parameters f, ω_g, and ω_s. Design of a thermally insensitive cavity for the passively Q-switched laser system means that a cavity must be set up to satisfy the conditions presented below.

First, the cavity must satisfy the stability condition defined by the ABCD matrix theory:

$$|(A + D)/2| \leq 1. \tag{6}$$

Second, to obtain a stable laser output, the laser system must continue to operate in the fundamental mode (TEM_{00} mode). If the radius of the pump beam in the gain medium is close to the average radius of the TEM_{00} mode, it can be used as a limiting aperture to reduce the higher-order modes and realize the fundamental-mode operation. Therefore, the cavity should satisfy the condition, where $\omega_l \leq \omega_p$.

Third, the TEM_{00} mode radius in the gain medium and the saturable absorber should be stable when the focal length of the thermal lens changes; this means that

$$\frac{d\omega_g}{df} \approx 0, \qquad \frac{d\omega_s}{df} \approx 0. \tag{7}$$

In fact, since the focal length of the thermal lens changes with the pump power, the cavity cannot satisfy the above condition over the entire pump range. Under the condition that the focal length of the thermal lens changes from f_1 to f_N with the pump power, we assume that

$$\left(\frac{d\omega_g}{df}\right)_{\text{average}} = \frac{1}{N}\left(\left|\frac{d\omega_g}{df_1}\right| + \left|\frac{d\omega_g}{df_2}\right| + \left|\frac{d\omega_g}{df_3}\right| + \ldots + \left|\frac{d\omega_g}{df_N}\right|\right), \tag{8}$$

$$\left(\frac{d\omega_s}{df}\right)_{\text{average}} = \frac{1}{N}\left(\left|\frac{d\omega_s}{df_1}\right| + \left|\frac{d\omega_s}{df_2}\right| + \left|\frac{d\omega_s}{df_3}\right| + \ldots + \left|\frac{d\omega_s}{df_N}\right|\right). \tag{9}$$

Obviously, to maintain a stable laser-system operation over the entire pump range, we must choose a cavity that ensures that both of these mean values are minimum.

3. Experimental Results and Discussions

The change in the focal length of the thermal lens of the Nd:YAG/Cr^{4+}:YAG/YAG composite crystal with increasing pump power was detected by the stable cavity method [12], and the results are shown in Fig. 6.

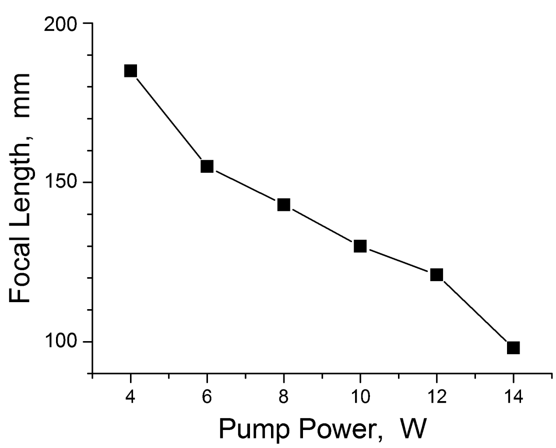

Fig. 6. Focal length of the thermal lens as a function of the pump power.

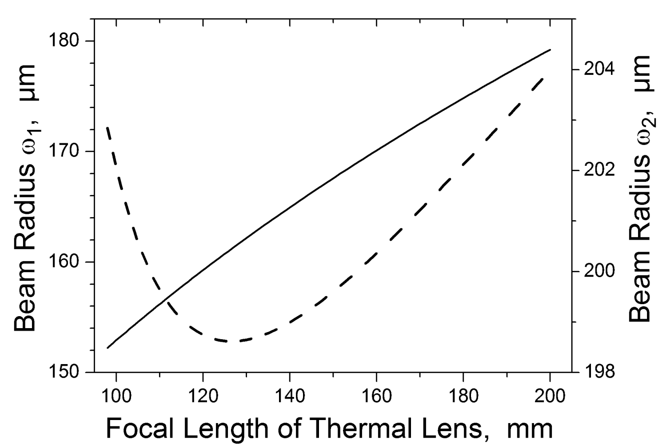

Fig. 7. Results of numerical simulation of the relationship between ω_l and f for cavity 1 (solid curve) and cavity 2 (dashed curve).

Based on the three conditions described above for the design of the thermally insensitive cavity and the test results for the thermal lens, a linear cavity was set up to obtain a stable passively Q-switched laser output. The structure is similar to that shown in Fig. 2 but with different parameters, namely, here, M1 is a plane mirror and M2 is a plano-concave mirror with a radius of curvature of 500 mm. M1 is HR-coated at 1,064 nm ($R > 99.6\%$), and the output coupler M2 is PR-coated at 1,064 nm ($R = 90\%$). The cavity length is 94 mm. The distances from M1 to the composite crystal and from the composite crystal to M2 are 18 and 64 mm, respectively.

The relationships between ω_l and f for the plane–plane cavity described above (cavity 1) and the optimized cavity (cavity 2) were calculated by the ABCD matrix theory, and the results are shown in Fig. 7.

After optimization, the beam radius became much more stable when the focal length of the thermal lens changes. This means that the influence of the temperature fluctuations is reduced. The extremum is at the point where $f \approx 130$ mm. In addition, the fundamental mode (TEM_{00} mode) radius is larger in the optimized laser cavity, and thus the laser system can easier operate in the fundamental mode ($\omega_l > \omega_p$).

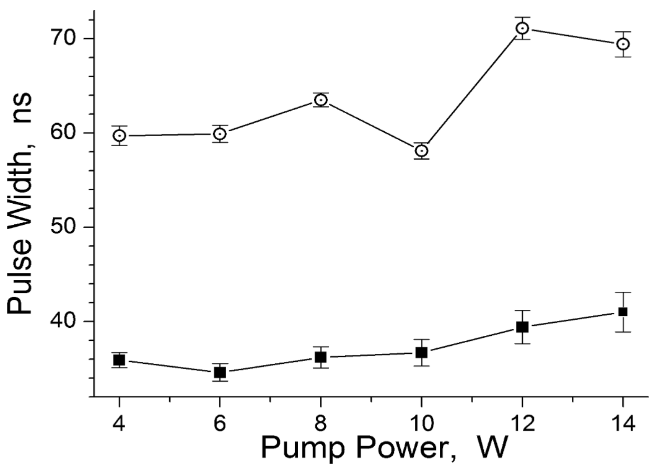

Fig. 8. Pulse width as a function of the pump power for cavity 1 (■) and cavity 2 (○).

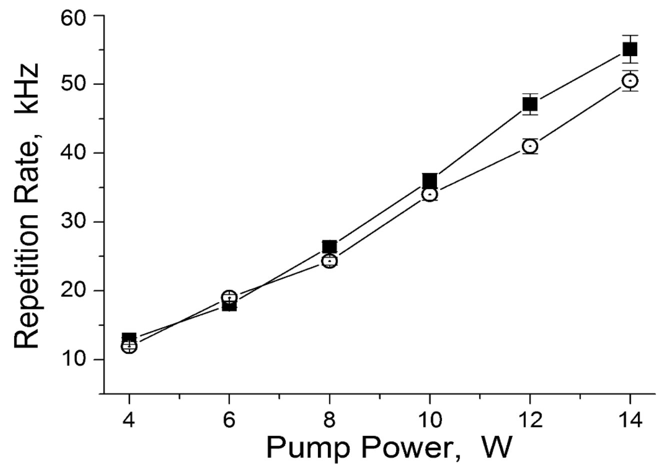

Fig. 9. Repetition rate as a function of the pump power for cavity 1 (■) and cavity 2 (○).

The pulse widths and repetition rates of the two cavities were detected by an oscilloscope with a bandwidth of 1 GHz and a sampling rate of 5 GS/s (Yokogawa DL9140). The average values and error values of the pulse widths and repetition rates are shown in Figs. 8 and 9, respectively. The results indicate that the laser output of the optimized cavity is more stable. Under a pump power of 8 W and a focal length of the thermal lens of 130 mm, a minimum relative pulse width fluctuation of 2.3% and a minimum relative repetition rate fluctuation of 3.5% were obtained, which is consistent with the numerical simulation results shown in Fig. 7.

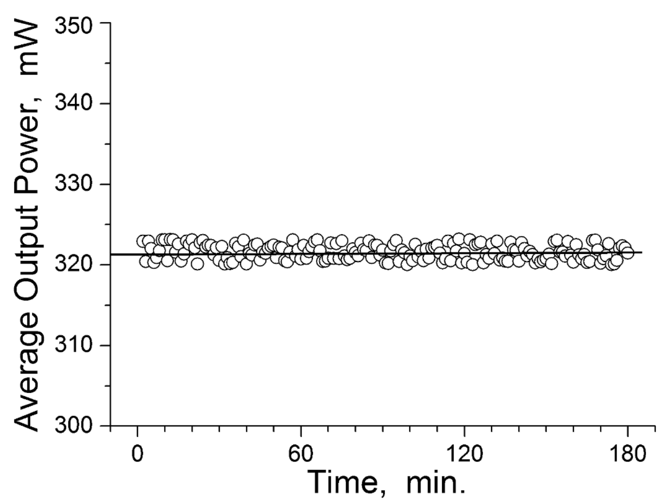

Fig. 10. Stability test results of the average output power from the optimized laser cavity.

The stability of the average output power from the optimized laser cavity at a pump power of 8 W was measured during 3 h. The fluctuation in the average output power was less than 1.8% (see Fig. 10).

Because no steps were taken to modulate the pump power, the pulse fluctuations were relatively high in the system under consideration. However, it was clear that the instabilities caused by temperature fluctuations can be reduced employing a suitable thermally insensitive cavity.

4. Summary

In this paper, we present the results of our study of pulse fluctuations in a passively Q-switched laser system caused by the thermal lens effect on the basis of theoretical analysis and experimental testing. We elaborated a method for the design of a thermally-insensitive cavity for the passively Q-switched laser system to reduce the instability of the laser output. Use of a suitable cavity structure and a Nd:YAG/Cr^{4+}:YAG/YAG composite crystal enabled us to reduce the fluctuations significantly. Under a pump power of 8 W, we obtained minimum relative fluctuations of the pulse width of 2.3% and a repetition rate of 3.5%, and the corresponding average output-power instability was less than 1.8%. Predictably, even lower instability can be reached if a synchronized pump is used.

Acknowledgments

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