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The effect of the depth of single longitudinal mode modulation in Q-switching pre-Pr^{3+}:YLF laser

Li Qing-Song [a], Zhu Ling-Xi [b], Zhang Xi-He [a], Dong Yuan [a,*], Yu Yong-Ji [a], Jin Guang-Yong [a]

[a] Chang Chun University of Science and Technology, The Key Laboratory of Jilin Province Solid-State Laser Technology and Application, Jilin Province 130022, People's Republic of China
[b] Chang Chun University of Science and Technology, Optical information Science and Engineering, Changchun, Jilin Province 130022, People's Republic of China

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A B S T R A C T

The single longitudinal mode (SLM) can be obtained under the condition of Q-switching pre-lase. In this paper, the model of Q-switching pre-lase is firstly established. Taking the Pr^{3+}:YLF laser as an example, the process of Q-switching pre-lase is simulated and optimized, then the optimized parameters and best output characteristics under different depth of SLM modulation are obtained. Comparing with the normal Q-switching laser, the SLM pulse energy can reach to 79.29%, the pulse width exceeds 16.45% and the depth of SLM modulation get to be 20. The results show that the Q-switching pre-lase output characteristics can be effected obviously by the SLM modulation depth, and the pulse energy and pulse width can be close to the normal Q-switching laser as long as the depth of SLM modulation is optimized.
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1. Introduction

The production of high-efficiency SLM pulse laser is a prerequisite issue for many laser applications in holography, transmission and so on. It can be realized by some methods [1–5]. The simplest method is introducing an etalon into the cavity, the loss of energy will be more than 60% although the SLM can be obtained easily. The circular cavity is also applied to select SLM but the complex and expensive design is a big problem, so we can not get high-efficiency SLM output. The third method of obtaining efficient SLM pulse laser is introducing a high quality signal from another laser in stead of the initial noise while the laser come into being [6–8], but this method need complex and accurate constructions. Q-switching pre-lase is specific technology that getting the seed signal from itself when the Q-switching is opened partly, in this time various modes compete fiercely each other and the central mode survive finally, it is amplified most after the Q-switching is opened completely at last. Sooy pointed that the SLM can be generated by the gain competition when the gain ratio of adjacent modes (depth of SLM modulation) greater than ten [9], it can be seen as the primary theory of the Q-switching pre-lase. And then many scientists obtained the SLM laser by using pre-lase technology [10–13]. However, the experiment results were not ideal because the lacking of perfect theory.

In this paper, the model of Q-switching pre-lase is constructed in order to obtain the high-efficient SLM output from the Pr^{3+}:YLF laser. Pr^{3+}:YLF laser is burgeoning from it is born for the unique emission waveband, it can simply get the laser at 607 nm, 639 nm, 747 nm [14–16], and 304 nm, 374 nm can be efficiently obtained after the double-frequency [17]. Generally speaking, the obtain of ultraviolet output need twice nonlinear frequency conversion, however, the ultraviolet output need only once nonlinear frequency conversion from the Pr^{3+}:YLF laser, so the conversion efficiency can be improved substantially, this is another reason of Pr^{3+}:YLF laser causing people to pay attention. In this paper, The Q-switching pre-lase is introduced to improve the SLM 607 nm output by the 445 nm pump light. The process of Q-switching pre-lase is simulated and optimized, the optimized parameters and best output characteristics are obtained under the different depth of SLM modulation. After our calculation and analysis, the results show that the Q-switching pre-lase output characteristics can be effected obviously by the SLM modulation depth.

2. Analysis of Q-switching pre-lase

As we all known, traditional Q-switching laser establishes from the noise and enhances among the different modes, but the stability of longitudinal mode is difficult to confirm because of the uncertainty of noise. Comparing to traditional Q-switching laser,

* Corresponding author.
E-mail address: laser_dongyuan@163.com (D. Yuan).

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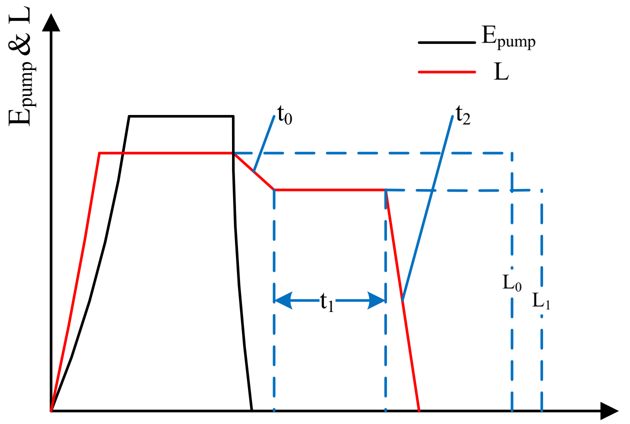

Fig. 1. The process of the Q-switching pre-lase.

the Q-switching pre-lase establishes from the seed signal by controlling the difference of loss between the Q-switching and the steady-state, and the character of the longitudinal mode is steerable to control. There need to point out that the modulation of the seed signal and oscillating amplifying process are the key of Q-switching pre-lase.

The process of the Q-switching pre-lase is shown as Fig. 1, where L is the two-way dissipative loss, L_0, L_1 are the loss of Q-switching and steady-state, E_{pump} is the injected energy from the pump system, t_0, t_1, t_2 are the duration of different stage (t_0, t_2 last for a extremely time and can be neglected).

The process of the Q-switching pre-lase can be divided into three stages after the pump energy E_{pump} injected:

(1) The stage of t_0 is the seed signal formative stage. The seed signal is generated from the moment that the Q-switching loss L_0 is switched to the loss L_1 slightly, then it is used to be instead of the initial noise. The feature of seed signal is related to injected pump energy E_{pump} and the value of pump energy is decided by Q-switching loss L_1 during the stage of t_0.
(2) The stage of t_1 is the steady-state stage or competition stage. Switch the loss from L_0 to L_1,the different longitudinal modes begin to compete, and the central mode has the maximum gain. The central mode would get the maximum and survive while the other mode would disappear gradually with the laser oscillation.
(3) The stage of t_2 is the output stage. It is same as normal Q-switching, the deviation is upper level population would be most saved to central mode. When the loss of steady-state is switched to zero, the SLM pulse laser would come into being and amplify.

3. The seed signal formative stage

Here the generation and the characters of seed signal are discussed. Firstly, the threshold population inversion and threshold energy can be get from the continuous four-level rate equation [18]:

$$\Delta n_t = \frac{L}{2\sigma l} \tag{1}$$

$$E_t = \frac{h\nu \Delta n_t \pi r^2 l}{\eta_0} \tag{2}$$

where $L = 0.04$ is the roundtrip dissipative optical loss, $\sigma = 1.4 \times 10^{-19}\,\text{cm}^2$ is the cross section of the central mode (607 nm) in the Pr^{3+}:YLF, $l = 9$ mm is the medium length, $\nu = 6.74 \times 10^{14}$ Hz is the frequency of the central mode, $r = 300\,\mu\text{m}$ is the cross section of oscillating beam, $\eta_0 = 1$ is the efficiency of pump, $h = 6.62617 \times 10^{-34}$ J s.

Set the Q-switching loss and steady-state loss $L_0 = XL$, $L_1 = KL$. The population inversion at the moment of Q-switching and steady-state can be given: $n_0 = X\Delta n_t$, $n_1 = K\Delta n_t$. While the loss is changed slightly, the population inversion of the seed signal is $\Delta n_0 = (X - K)\Delta n_t$. (X−K < 1,if X−K > 1, the laser would be produced.)

When the loss is switched to L_0 and the injected energy can be described as $E = XE_t$, the full width at half maximum (FWHM) of the seed signal oscillation can be given:

$$\frac{n_0}{\left(\frac{\Delta\nu_s}{2}\right)^2 + \left(\frac{\Delta\nu_D}{2}\right)^2} = \frac{\Delta n_t}{\left(\frac{\Delta\nu_D}{2}\right)^2} \tag{3}$$

The equation can be get after settle the Eq. (3) is shown in Eq. (4):

$$\Delta\nu_s = \sqrt{X-1}\,\Delta\nu_D \tag{4}$$

$$\Delta\nu = \frac{c}{2\left[l_0 \cdot n + (l_0 - l)\right]} \tag{5}$$

where $\Delta\nu_D = 6 \times 10^4$ MHz is the FWHM of Pr^{3+}:YLF spontaneous radiation, $\Delta\nu_s$ is the FWHM of the seed signal oscillation when the system is at the state of Q-switching, $\Delta\nu$ is the FWHM which is limited by the specified length resonant cavity, the number of longitudinal mode is $N = \frac{\Delta\nu_s}{\Delta\nu}$ (round numbers), $n = 1.45$ is the refractive index of Pr^{3+}:YLF, $l_0 = 20$ mm is the length of the resonant cavity.

Pr^{3+}:YLF laser is solid laser which is belong to homogeneous broadening, there need to introduce the atomic linear function of homogeneous broadening to describe the gain difference:

$$\tilde{g}(\nu, \nu_0) = \frac{g(\Delta\nu_0)}{2\pi}\left[(\nu - \nu_0)^2 + \left(\frac{\Delta\nu_s}{2}\right)^2\right]^{-1} \tag{6}$$

where g($\Delta\nu_0$) is the maximal gain of central mode which is a relative constant and decided by the laser itself. The center mode and the adjacent mode almost occupy the most gain in the competition and the gain of the other mode can be ignored, then the ratio of the gain between adjacent ν_m mode (there are two symmetrical modes nearby the central mode, and take one as an example) and central ν_n mode can be get from Eq. (6):

$$\frac{g_m}{g_n} = \frac{\left[(\nu_n - \nu_0)^2 + \left(\frac{\Delta\nu_s}{2}\right)^2\right]}{\left[(\nu_m - \nu_0)^2 + \left(\frac{\Delta\nu_s}{2}\right)^2\right]} \tag{7}$$

Set the mode $\nu_n = \nu_0$ as the central mode and $\nu_n – \nu_m = \Delta\nu$, then put the Eqs. (4), (5) in (7), Eq. (8) shows the relation between the injected energy and the ratio of the gain between adjacent ν_m mode and center ν_n mode:

$$\frac{g_m}{g_n} = \frac{1}{1 + \frac{4}{X-1}\left(\frac{\Delta\nu}{\Delta\nu_D}\right)^2} \tag{8}$$

From Fig. 2, it can be seen that the ratio of the gain between adjacent ν_m and center ν_n mode come to be equal with the injected pump energy increasing which is decided by the loss of Q-switching (The loss of Q-switching is almost set to be infinity in some papers, where we set it constant to be convenient for the calculation.). This is because the number of longitudinal mode

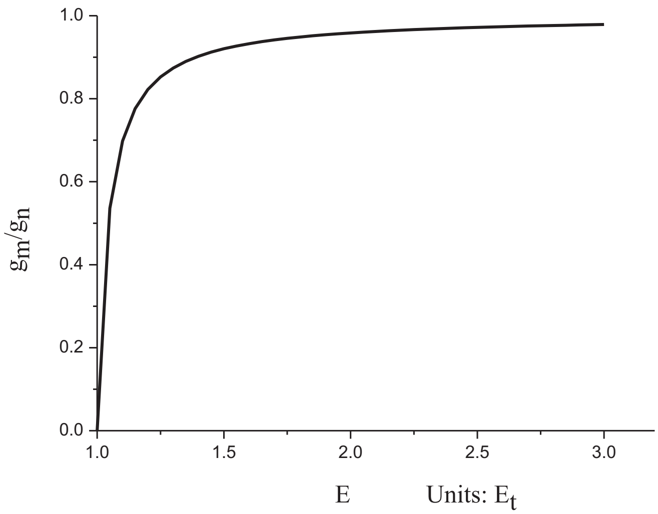

Fig. 2. The injected pump energy E_{pump} and the ratio of the gain between v_m and v_n mode, where the units of injected energy X is E_t.

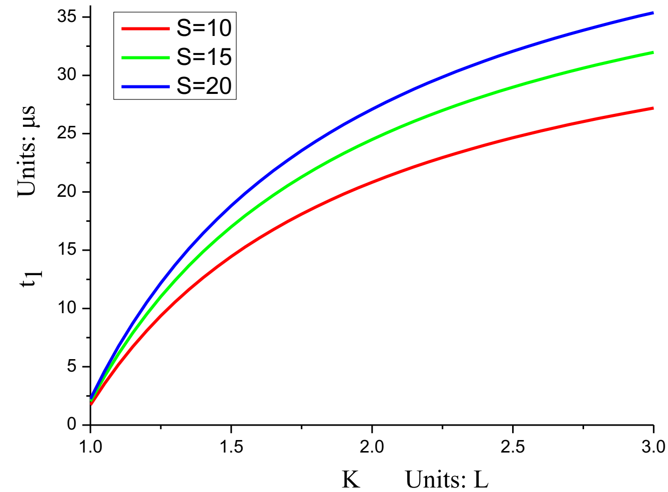

Fig. 3. The steady-state loss K and the steady-state time t_1 when the SLM is achieved under different depth of mode modulation S.

increased and the different modes become to be equal gradually when increasing the injected pump energy. It means that the more time should be costed on steady-state stage to keep the different longitudinal mode competing in order to obtain the SLM laser. So pre-lase is fit for low-energy laser to get the SLM. In some high-energy laser, the high-energy SLM output can be acquired by the combination of the mode selection device and pre-lase technique, because the FWHM get to be broaden a lot and the time of steady-state cost more than upper level lifetime when the injected energy is higher enough. From the above, it can be seen that the mode feature of seed signal is decided by the upper level population which is effected by the Q-switching loss or the inject energy.

4. The steady-state stage

The traditional laser is generated from the noise and amplified in resonant cavity, however the seed signal can be generated directly to replace the noise after the loss be switched a little in pre-laser.We need to find the best time at which not only the longitudinal mode get achieved but also the output power of center v_n mode reach the maximum.

(1) Time modulatioN OF SLM

The ratio of the output power between adjacent v_m and center v_n mode which is the depth of SLM can be obtained from W.R. Sooy's theory:

$$\frac{P_n}{P_m} = e^{t_1 cK\Delta n_t \sigma_n \frac{l}{l_0}(1-g_m/g_n)} \tag{9}$$

$P_n/P_m = 10$ is the standard depth of SLM in some papers, but some scientists found stability of SLM was not enough good and the depth of SLM is needed to modulated deeper to get better stability. From Eq. (9), we can intuitively see the feature of SLM get better when the value of depth is modulated to larger number.

Here get $P_n/P_m = S$, $S = 10, 15, 20$, and the relation between the steady-state loss and the time at which the SLM be achieved can be shown in Eq. (10):

$$t_1 = \frac{\ln S}{cK\Delta n_t \sigma_n \frac{l}{l_0}\left(1 - \frac{g_m}{g_n}\right)} \tag{10}$$

From Fig. 3, we can see it should cost more time to keep the competition going on while we want to acquire the SLM laser which have higher quality and energy. It should be noted that the time of steady-state must be longer than the time when SLM modulation is just achieved, and it is also limited by the upper level lifetime. If the upper level lifetime is exceeded, spontaneous radiation should be considered. Although spontaneous radiation is often beneficial for normal laser but it is harmful to SLM laser and make the energy of SLM laser fall off quickly.

(2) Energy optimization of SLM

The energy optimization of SLM is the process that the gain of center v_n mode get the maximum from the system and gain saturation is attained. When the gain saturation is reached, the gain is equal to the loss and the power of central mode get a steady value in a flash.

Then the gain can be described after Q-switching:

$$G = e^{2\sigma_n X\Delta nl}$$

When the central v_n mode get gain saturation at initial time t_1, the loss is equal to the gain and can be given:

$$L_k = G_k = e^{2\sigma_n K\Delta nl}$$

The population inversion consumption of the central v_n mode which is generated by the seed signal oscillation and amplification after stage t_1 can be get in Eq. (11):

$$n_+ = \frac{\Delta n_0}{N}\left[\left(\frac{G}{L_k}\right)^{\frac{1}{2}}\right]^q \tag{11}$$

where $(\frac{G}{L_k})^{\frac{1}{2}} = e^{\sigma_n(X-K)\Delta nl}$ is approximate to gain factor of single trip, because the loss is fixed and the gain reduces erratically with the timekeeping, $\Delta n_0/N$ is the inversion population of central mode in the seed signal formative stage(because the mode competition do not begin and the different modes almost get the same gain), $q = ct_1/2l_0$ is the number of circulation.

In the process of oscillation, the total population inversion would be distributed into two parts: a part is used to conquer the loss of steady-state, the other part is used to gain the seed signal and make the central mode get the most inversion population which is the effective population inversion of central mode. The effective population inversion supply to the center v_n mode by the system is given:

$$n_- = n_1 \cdot \left(\frac{p_n}{p_n + 2p_m}\right)\left(\frac{1}{1 + \left(\frac{L_k}{G}\right)^{\frac{1}{2}}}\right) \tag{12}$$

In Eq. (12), n_1 is the total gain population inversion provided by the system, $\frac{p_n}{p_n+2p_m} = \frac{S}{S+2}$ is the factor of mode discrimination, $\frac{1}{1+\left(\frac{L_k}{G}\right)^{\frac{1}{2}}}$ is the factor that describes the ratio between the effective gain and the whole population inversion of central mode.

There is the relation between and n_- in the process of oscillation, the efficiency of effective gain $\eta = \frac{n_+}{n_-}$ can be get as the Eq. (13) shown:

$$\eta = \frac{S+2}{S \cdot N}\frac{(X-K)e^{\sigma_n \Delta n c t_1 (X-K)\frac{l_0}{l}}\left(1 + e^{\sigma_n (K-X)\Delta n c t_1 \frac{l_0}{l}}\right)}{K} \tag{13}$$

The state of gain saturation in laser can be known intuitively from the value of η:

a. $\eta < 1$, gain saturation is not reached, the population inversion of v_n mode do not get the extreme value.
b. $\eta = 1$, gain saturation is reached, the population inversion of v_n mode get the extreme value.
c. $\eta > 1$, gain saturation is exceeded, the population inversion of v_n mode go over the extreme value and get to decline quickly.

From Fig. 4, it can see that set the value of loss between the Q-switching and steady-state reasonable is helpful to acquire the high quality SLM (S=20), and the time of steady-state would be extended more longer than the low quality SLM which can be seen from the Fig. 3.

Set X=3, it means the injected energy triples the threshold value, then the final gain quantity of central mode is shown in Fig. 5. It can be found that the effective population increases when S set to be bigger and the loss of steady-state get close with the loss of Q-switching. The reason is rational seed signal could be amplified to larger value and the SLM modulation could get achieved at the same time. If set the seed signal too small, the SLM modulation could get achieved but the gain of central mode couldn't get the maximum. If set the seed signal too big, not only the SLM modulation couldn't get achieved, but also the gain of central mode would exceed the maximum and fall quickly. It can be obtained that select the suitable loss and best time of steady-state decides the final depth of SLM which impacts on the output characteristics and stability of SLM.

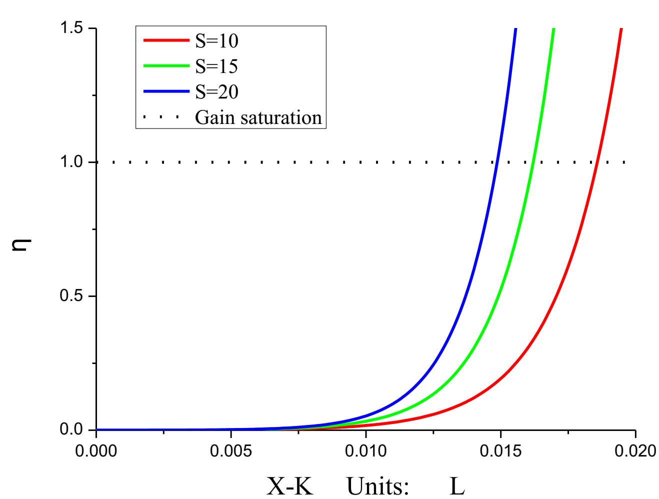

Fig. 4. The state of gain saturation is shown when the difference value between the Q-switching loss and steady-state loss is set under different depth of SLM modulation S=10, S=15, S=20.

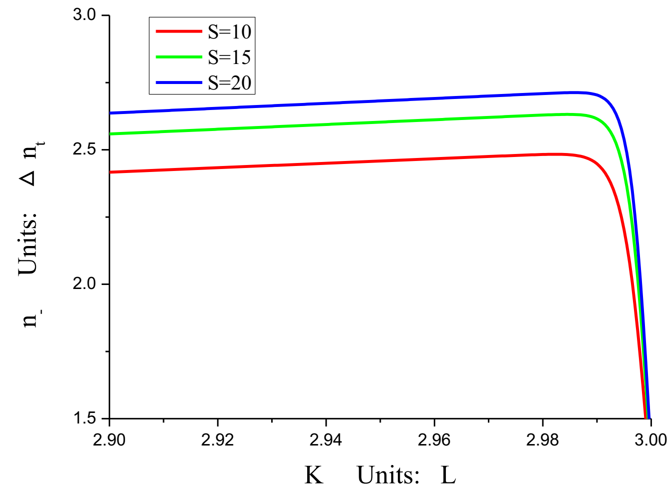

Fig. 5. The effective population inversion of v_n mode is shown when the steady-state loss K is set in different values, where the units of K is L, the units of n is Δn_t.

5. Output stage

We can get the different value of n_+ from the Section 4 when the gain saturation is reached and the depth of SLM get 10, 15, 20. In fact, the value of n_+ is equal with the small signal gain value Z which shows the rate of between inverted population and the threshold value in the J.JOHN's theory [19]. We get the optimized parameter n_+ into the Eqs. (14) and (15) which show the relation between output characteristics and small signal gain value Z:

$$E = \frac{Ah\nu L}{2\sigma\gamma}(z - 1 - \ln z) \tag{14}$$

$$\tau_p = \frac{2l}{cL}\left[\frac{\ln z}{z\left(1 - \frac{z-1}{z \ln z}\left(1 - \ln\frac{z-1}{z \ln z}\right)\right)}\right] \tag{15}$$

where $A = \pi r^2$ is the laser beam cross section, $r = 300$ μm is the radius of cross section, E is the energy of single pulse, τ_p is the width of pulse. The output characteristics of normal Q-switching and pre-lase Q-switching can be computed when the inject energy $E_{pump} = X \cdot E_t = 540$ μJ, then the optimized results under different depth of SLM modulation are shown in Table 1:

From the Table 1, the single pulse energy is lower and pulse width is bigger than the normal Q-switching laser, the reason is that the a part of inversion population wastes on overcoming the cavity loss in the pre-lase process. The optimized result is that the single SLM pulse energy can reach 79.29%, the pulse width exceed 16.45% compared with the normal Q-switching while we get the

Table 1
The comparison between normal Q-switching and pre-lase Q-switching in the different depth of SLM modulation.

	K (L)	t_1 (μs)	Z (Δn_t)	E (μJ)	τ_p (ns)
Normal Q-switching	–	–	3.0	119.17	12.199
Pre-lase Q-switching					
S=10	2.9814	27.112	2.4831	75.835	16.367
S=15	2.9838	31.899	2.6315	87.781	14.9
S=20	2.9851	35.295	2.7126	94.491	14.206

depth of SLM to 20. It is quite close to the normal Q-switching laser. The analysis shows that the advantage of pre-lase is the SLM can be acquired without any device and the power approach the normal Q-switching than other way to select SLM. The disadvantage is that the stage of steady-state cost a long time to keep different modes competition which cause number of pulse is less than the normal Q-switching laser in the same time and the average power get lower than the normal Q-switching laser in high repetition frequency laser.

6. Discuss and conclusion

In this paper, the Q-switching pre-lase is optimized and the depth of SLM is modulated to acquire the high stability SLM laser for the first time to our best knowledge. It is a effective way to obtain the high-efficiency SLM pulse Pr^{3+}:YLF laser, we can get the befitting depth of SLM to satisfy the different requirements. From this paper, set the loss of steady-state reasonable and extend the time of steady-state are the best way to acquire the higher single pulse energy and the shorter pulse width, and it would cause the average power of laser less a little.

Finally, We get the depth of SLM $S=20$ and the single pulse energy $E = 94.491\ \mu J$, pulse width $\tau = 14.206$ ns when $t_1 = 35.295\ \mu s$. Comparing with the depth of SLM $S=10$, it cost more time on the stage of steady-state, but the single pulse energy and pulse width get effectively optimized. It is proved that the single pulse energy and pulse width of pulse laser is get better when the depth of SLM is modulated to be deeper in Q-switching pre-laser. The optimization method can be used in most solid laser to solve the question that a high-efficiency SLM pulse get acquired through the simple control of the loss and time and avoid adding any extra loss device. We have further considered that there must be the best parameters set which can make the average power get to the peak value and the next research focus is the high power SLM pulse laser by using the pre-lase technique.

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